Introduction to Belle & Belle II

and a choice subject from recent physics highlights

Youngjoon Kwon
Yonsei Univ.

Saga-Yonsei Joint Workshop XIX, Jan. 19, 2023

THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

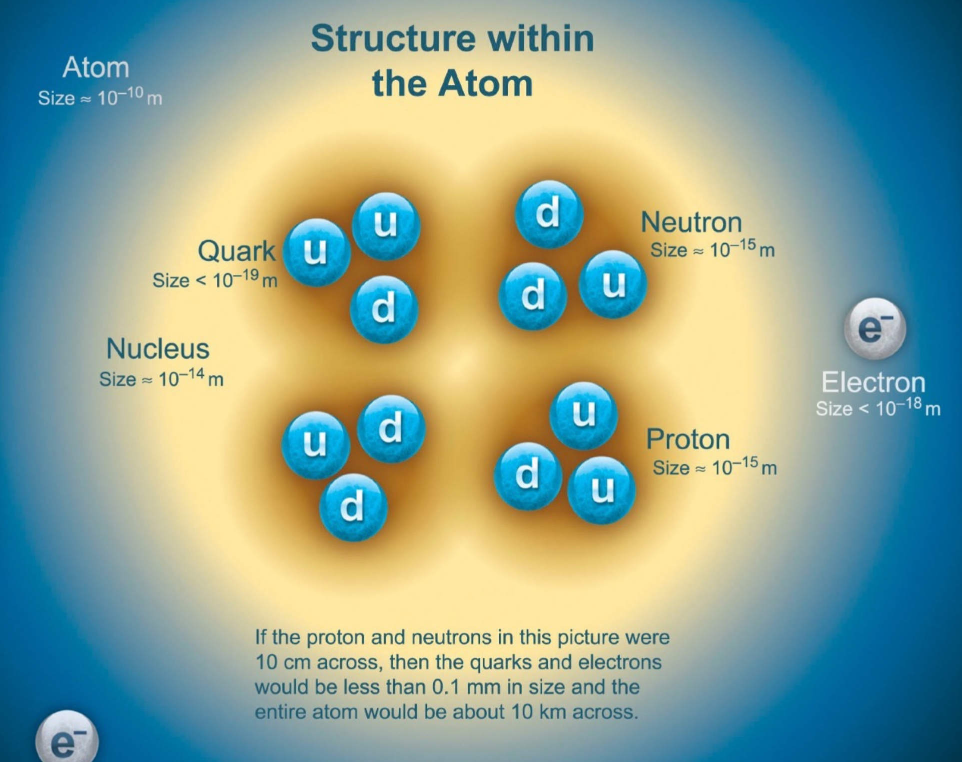
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

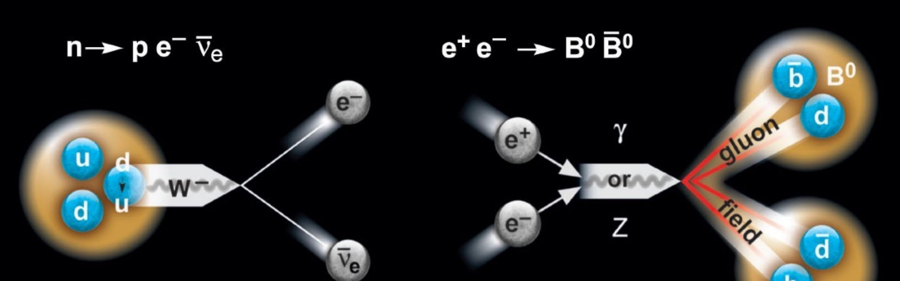
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

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What

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Belle & Belle II

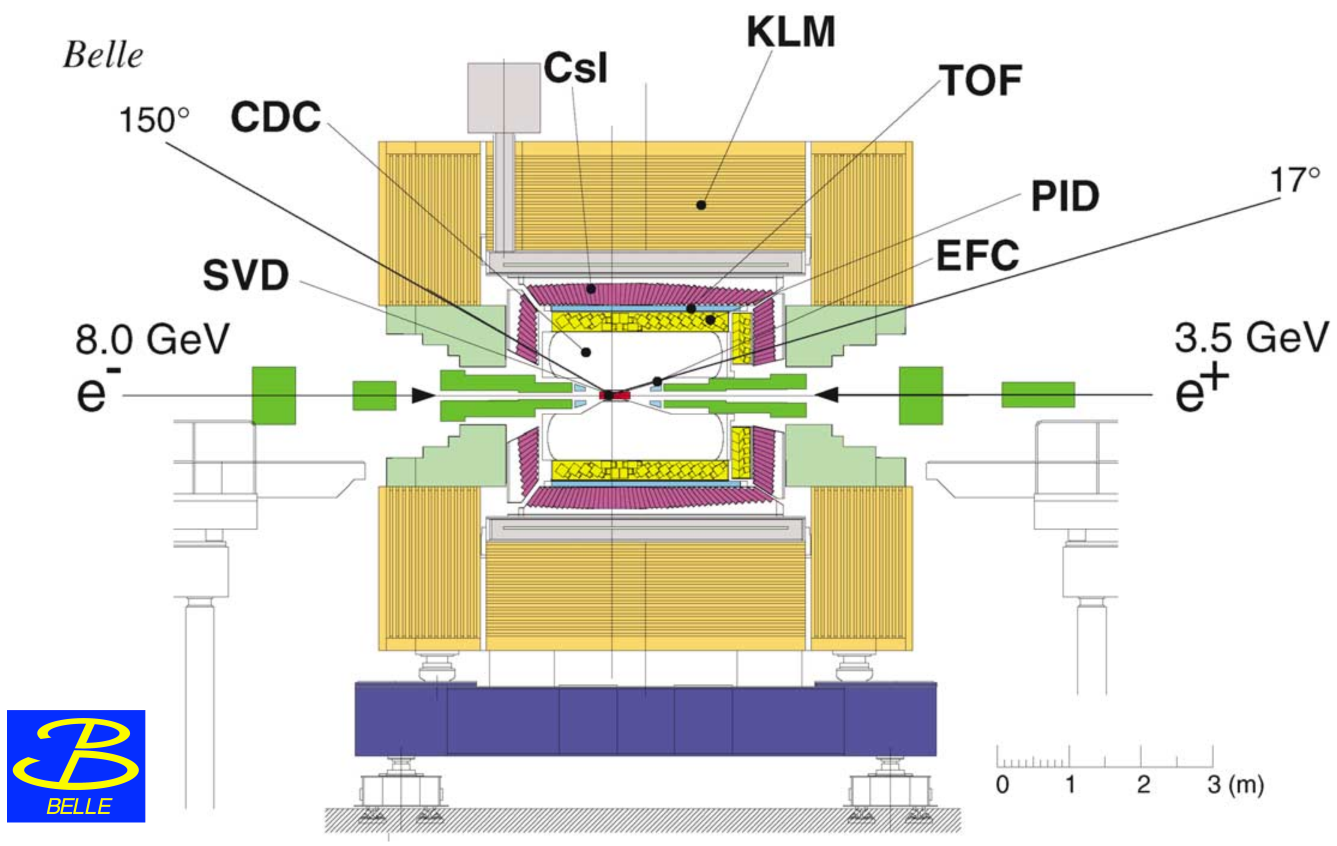
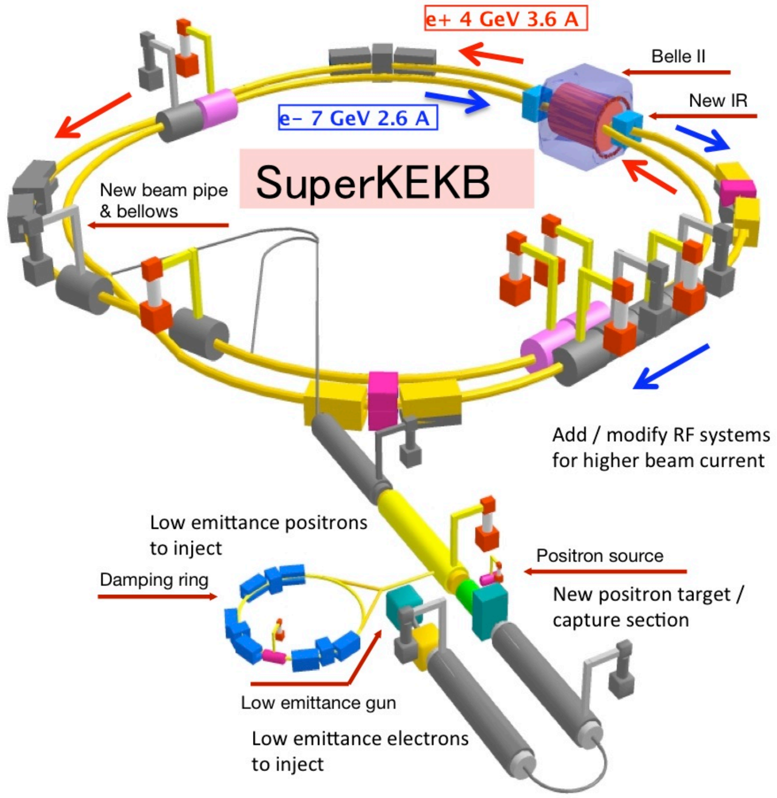
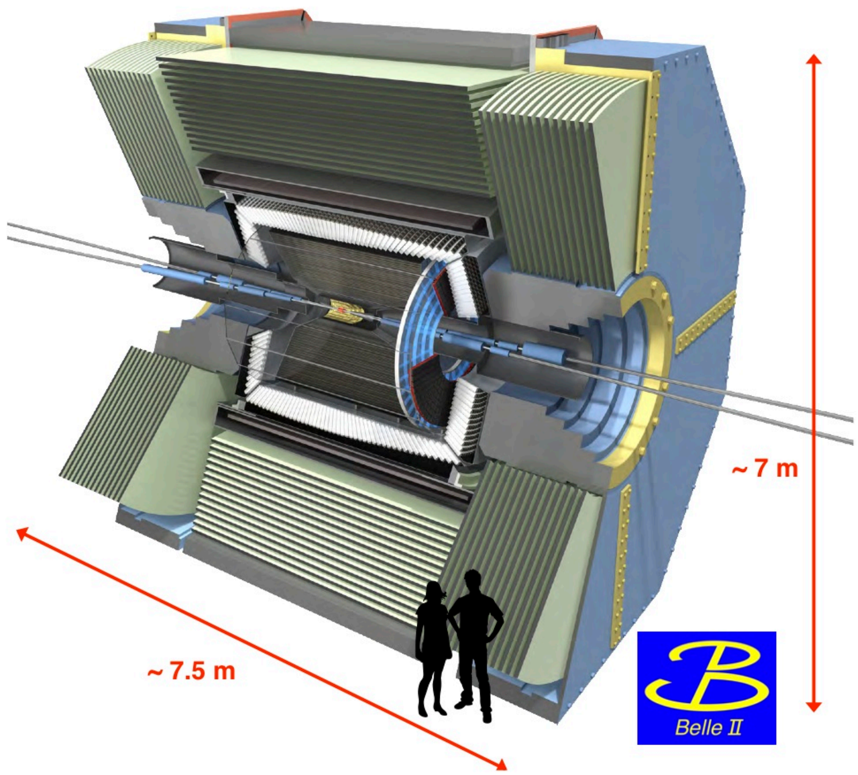


Fig. 1. Side view of the Belle detector.

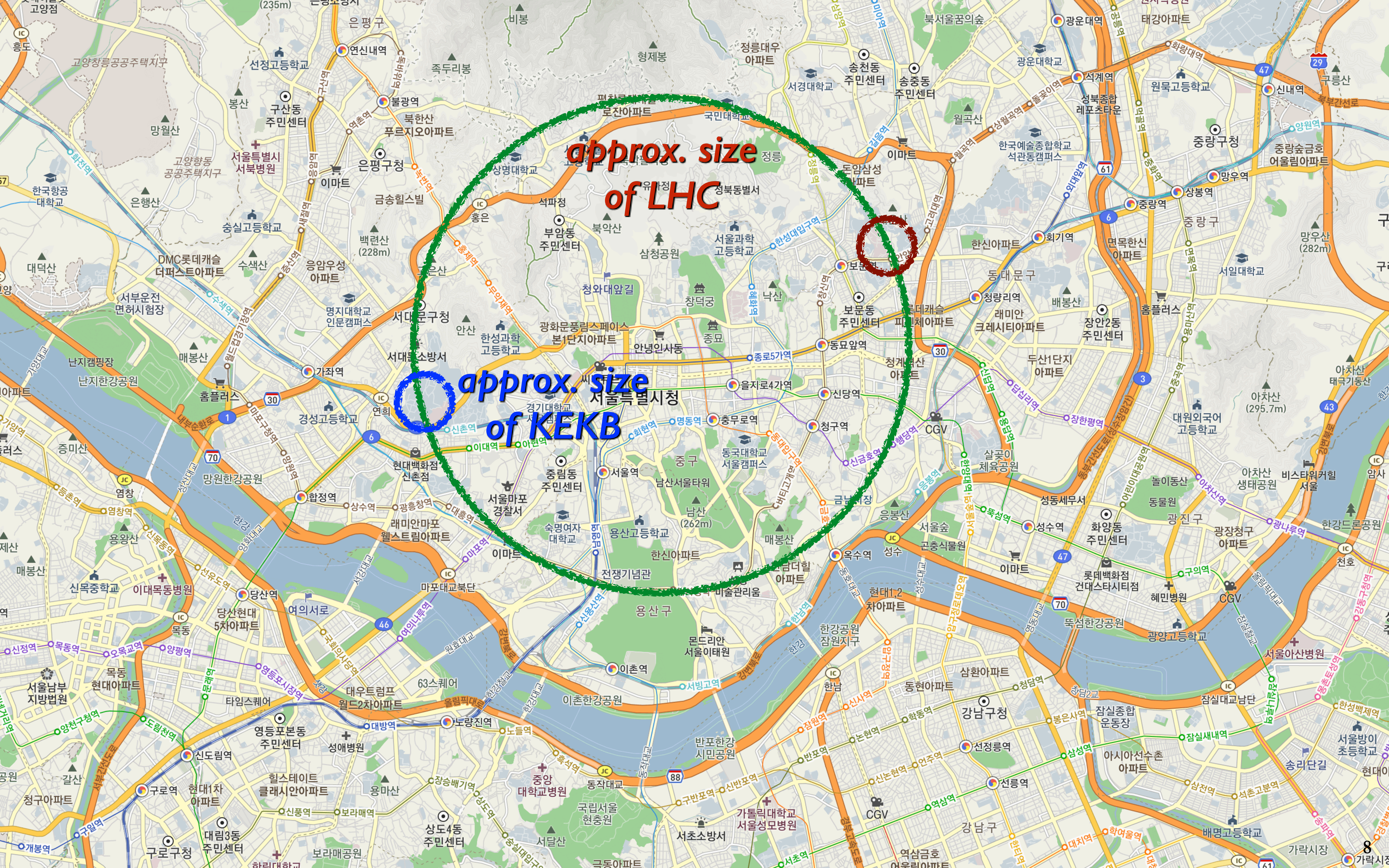




Belle & Belle II

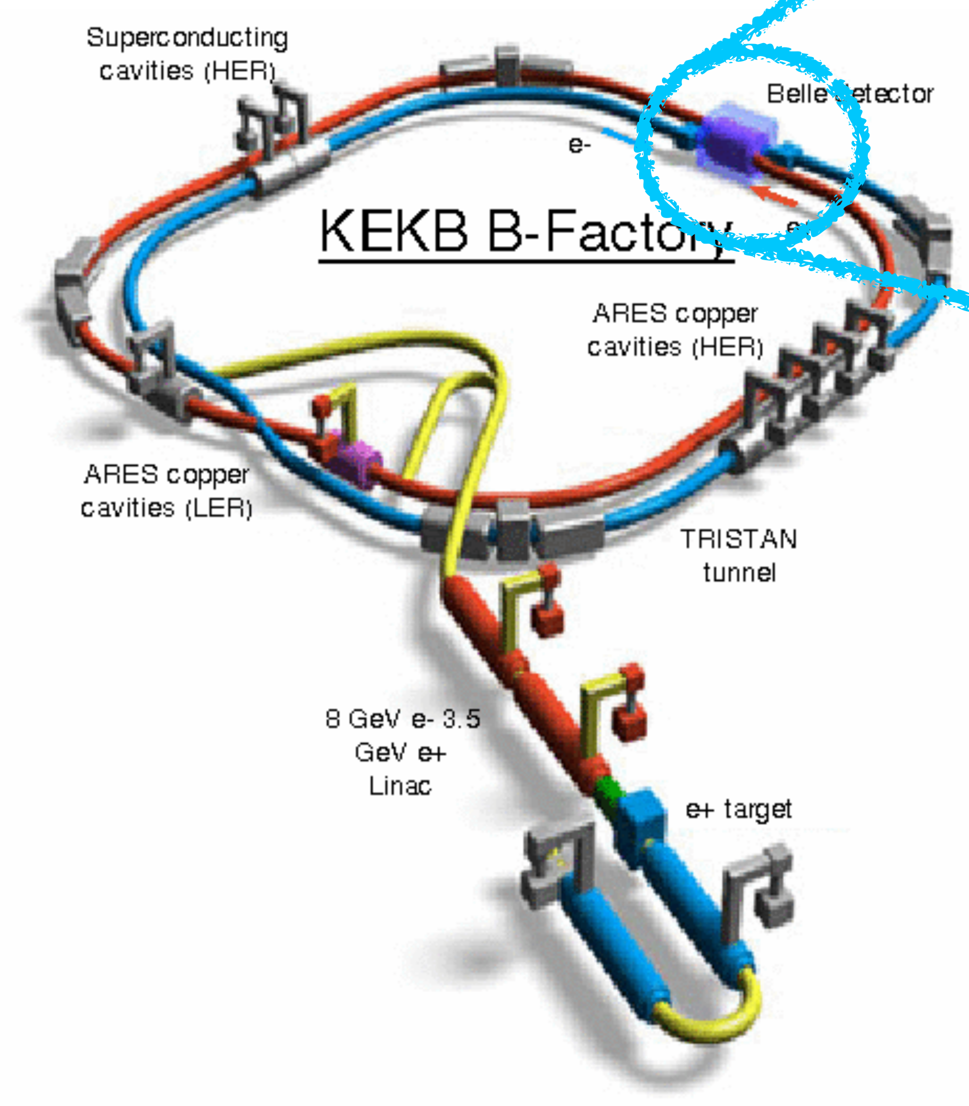
- mainy for CP violation in B-meson system
  - CP violation — a necessary condition for BAU
- the Belle experiment
  - took data during 1999-2010 using e+ e- collider KEKB at KEK, Japan
  - produced more than 600 physics papers (*still active and strong!*)
  - observed CP violation in the B-meson system (for the first time, along with BaBar) & confirmed Kobayashi-Maskawa theory ➔ 2008 Nobel Physics prize
  - ~450 physicists from 22 countries
  - total budget: approx. US$ 300 M

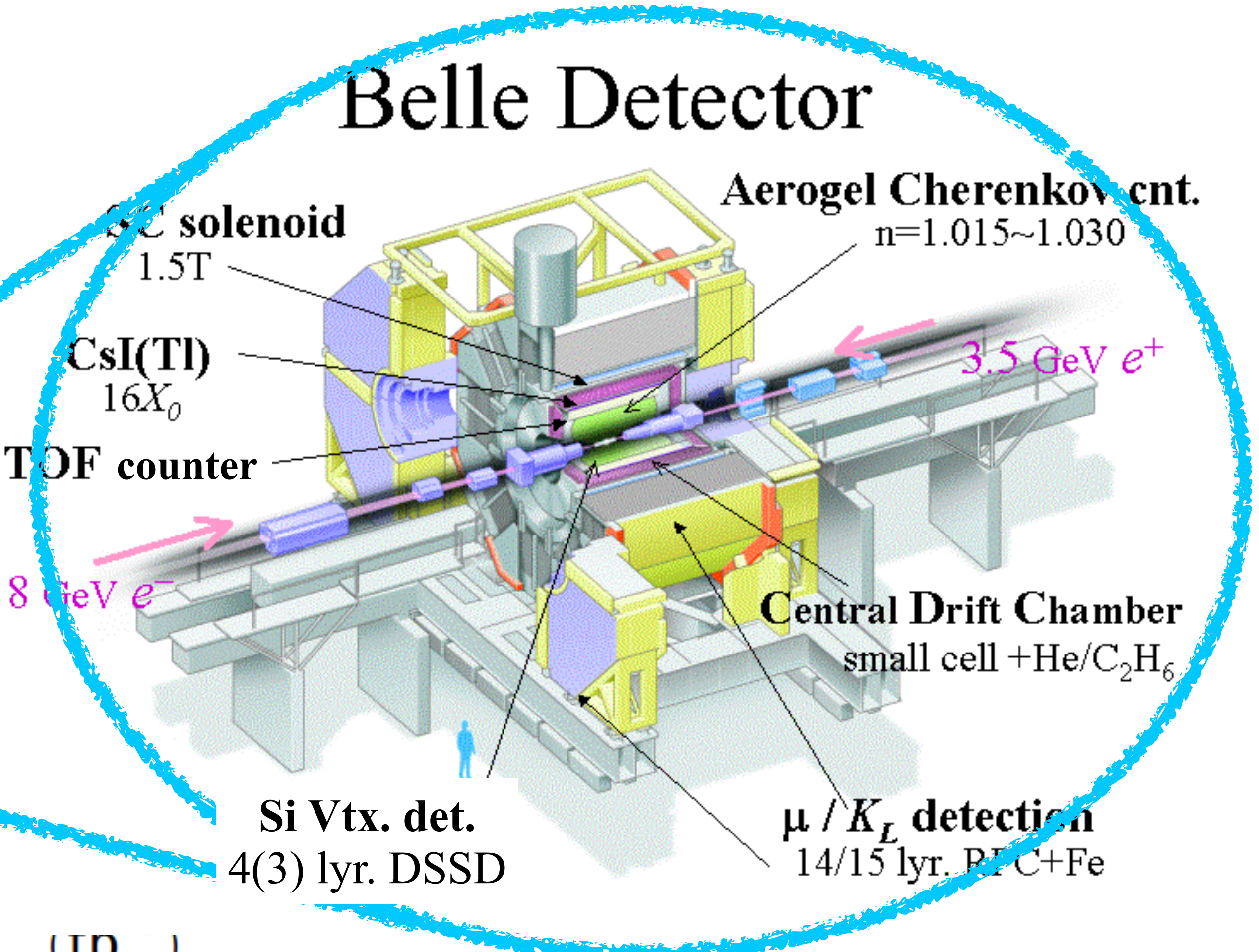

Mt. Tsukuba
BELLE II
~ 1 km
~ 1.5 km
KEKB Ring
Damping Ring
Linac
KEK Tsukuba Campus


approx. size
of LHC
approx. size
of KEKB

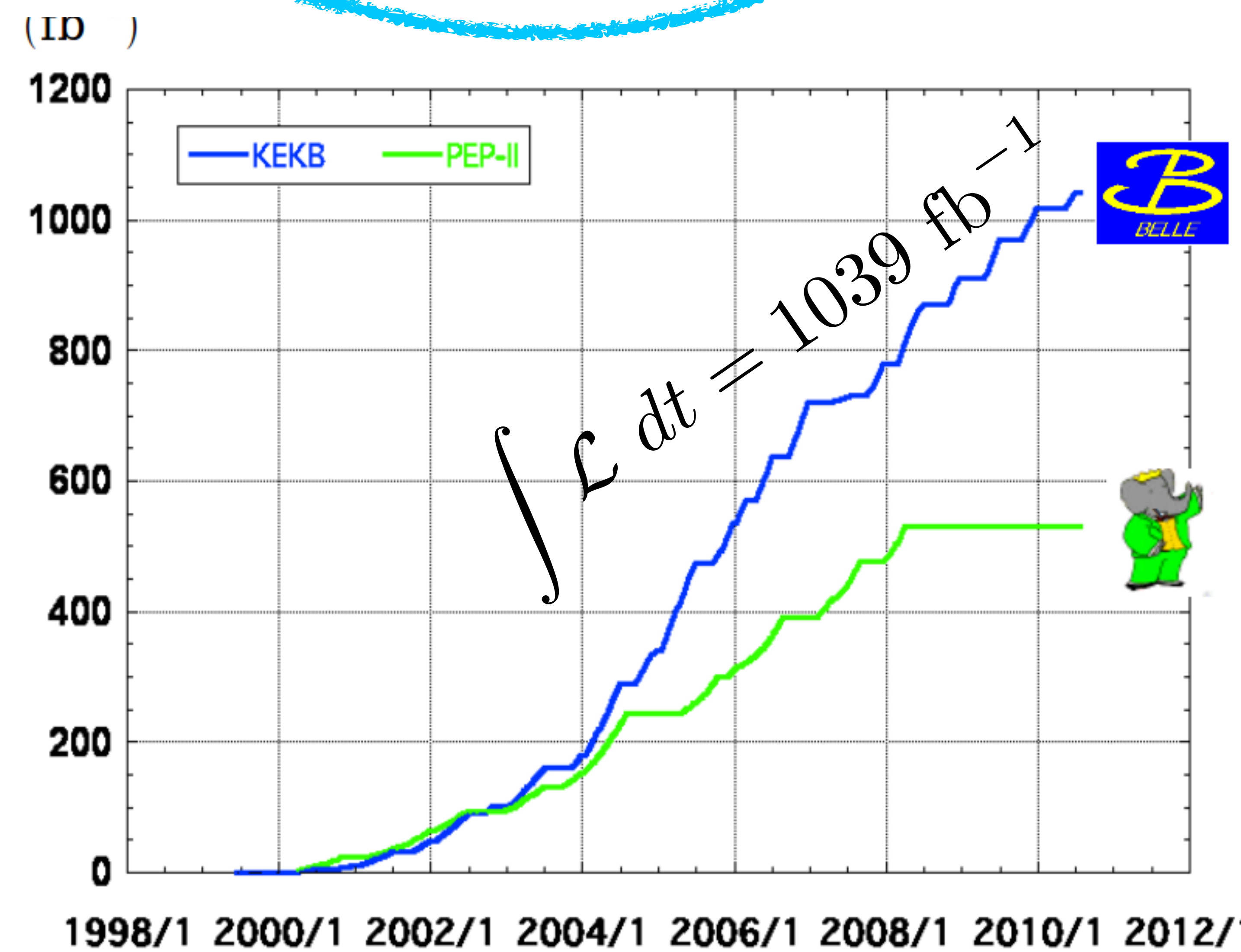
22 countries
100 institutions
~450 members

$$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$$





$$e^- \xrightarrow{\textbf{8 GeV}} (\star) \xleftarrow{\textbf{3.5 GeV}} e^+$$

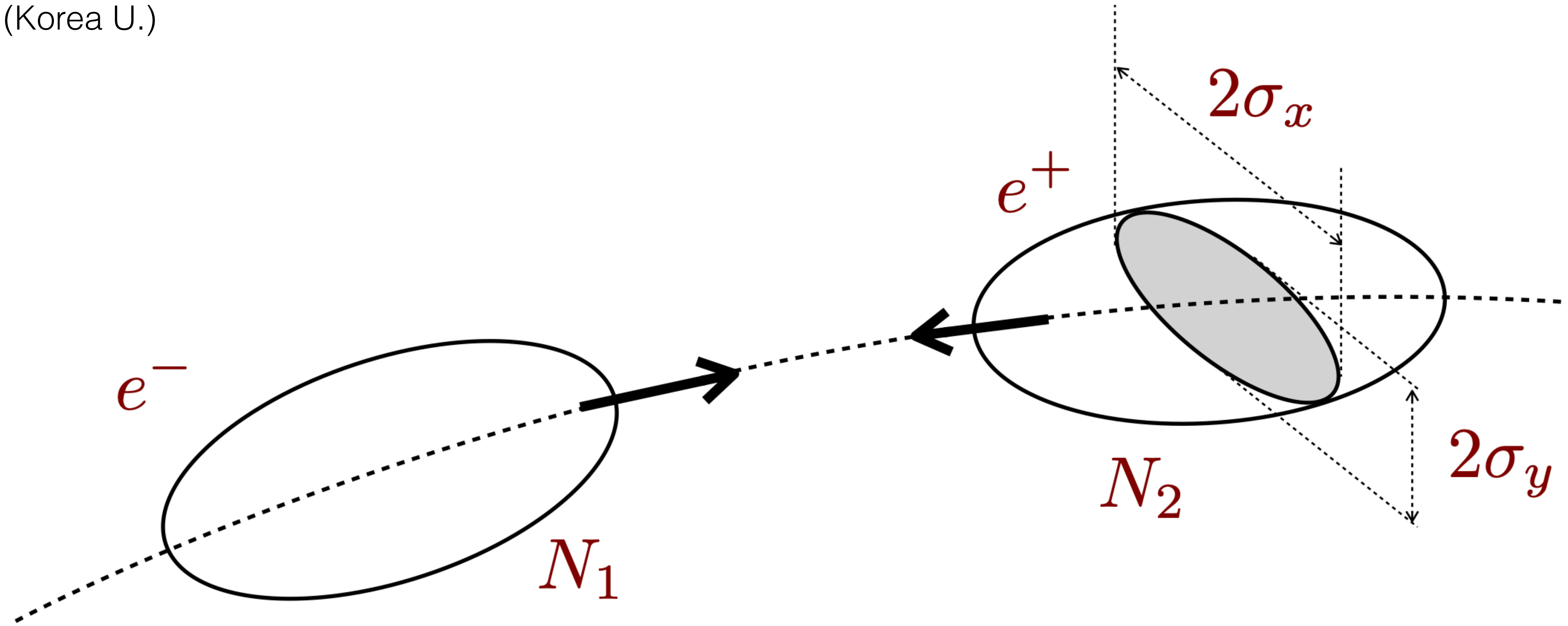


> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Luminosity 101

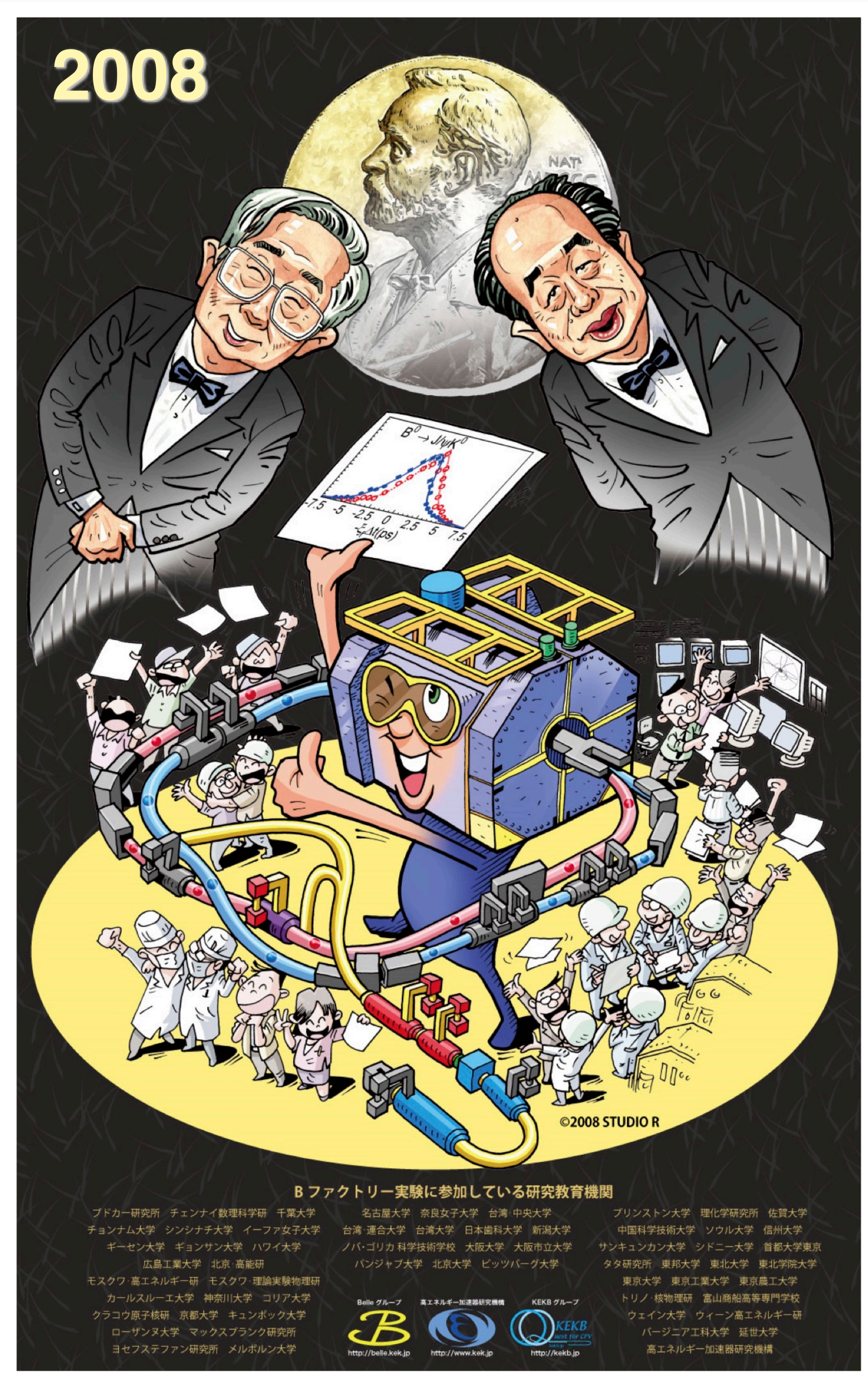
Figure from Prof. E. Won (Korea U.)



Event rate (dN_p/dt) for a particular process "p"

$$\frac{dN_\mathrm{p}}{dt} = \sigma_\mathrm{p}\mathcal{L}$$

$$\mathcal{L} = \frac{1}{4\pi e^2 f_\mathrm{rev} b}\,\frac{I_- I_+}{\sigma_x \sigma_y}$$



Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

Belle → Belle II

still not solved

- CP violation from KM hypothesis is not large enough to explain the matter-antimatter asymmetry in our Universe

  ➔ *We need New Physics!*

- The origin of the Flavor structure of the Standard Model is totally unknown

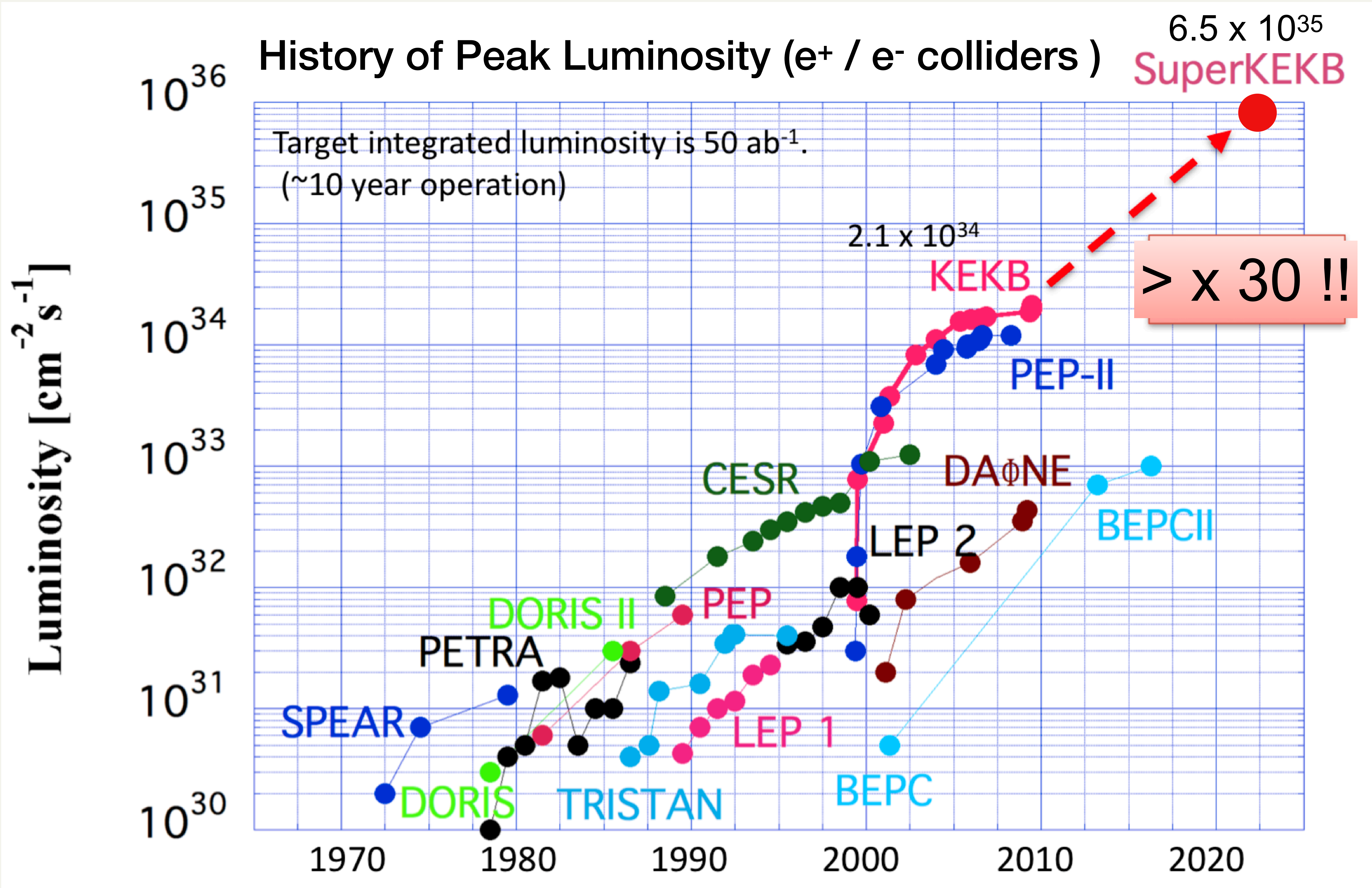
upgrade Belle —> Belle II

- KEKB is upgraded to SuperKEKB (goal: x30 peak luminosity)
- aiming at x50 total data size
- Belle detector is also upgraded to Belle II

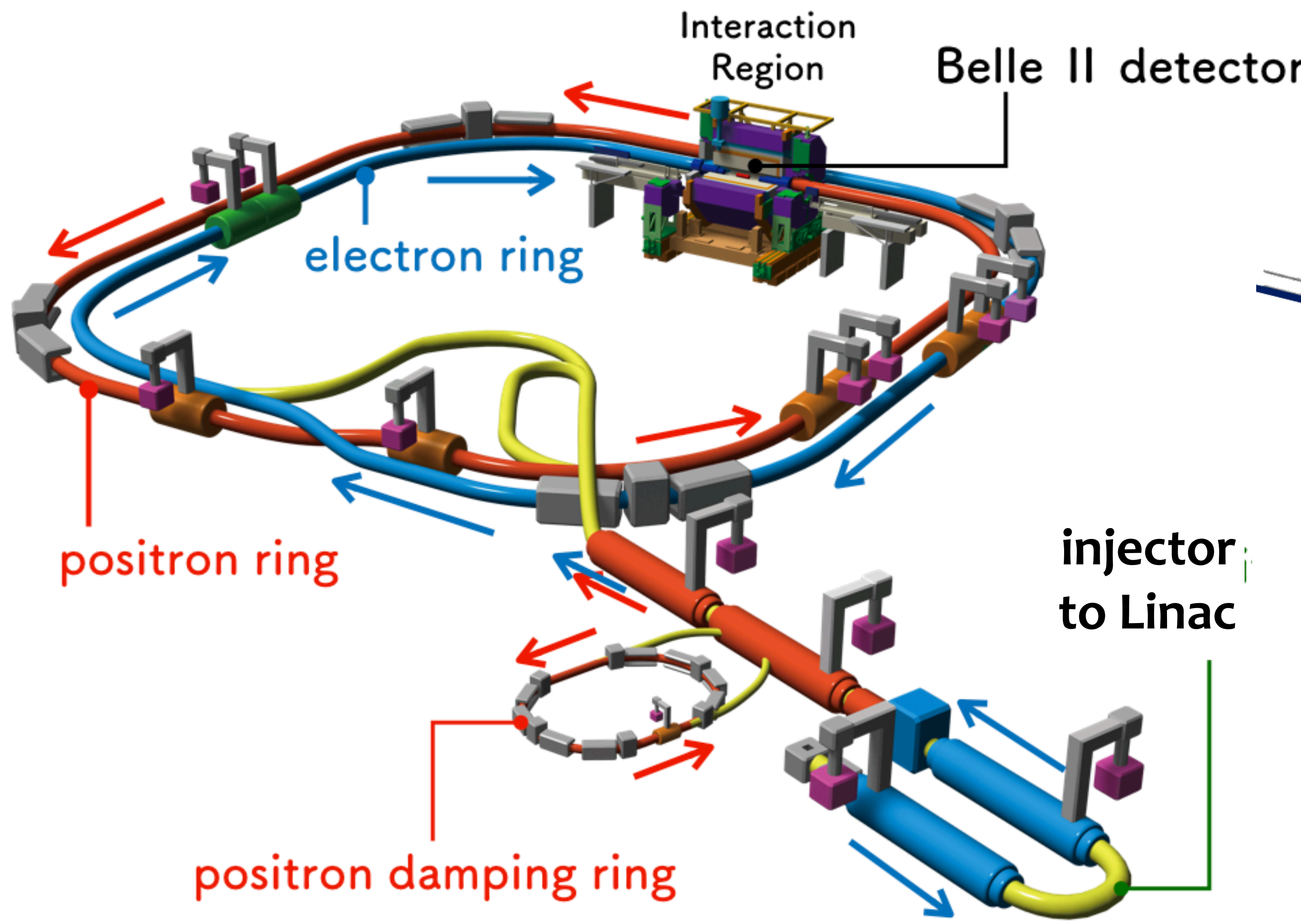
$$\mathcal{L}_{\text{peak}} = 6.5 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$$

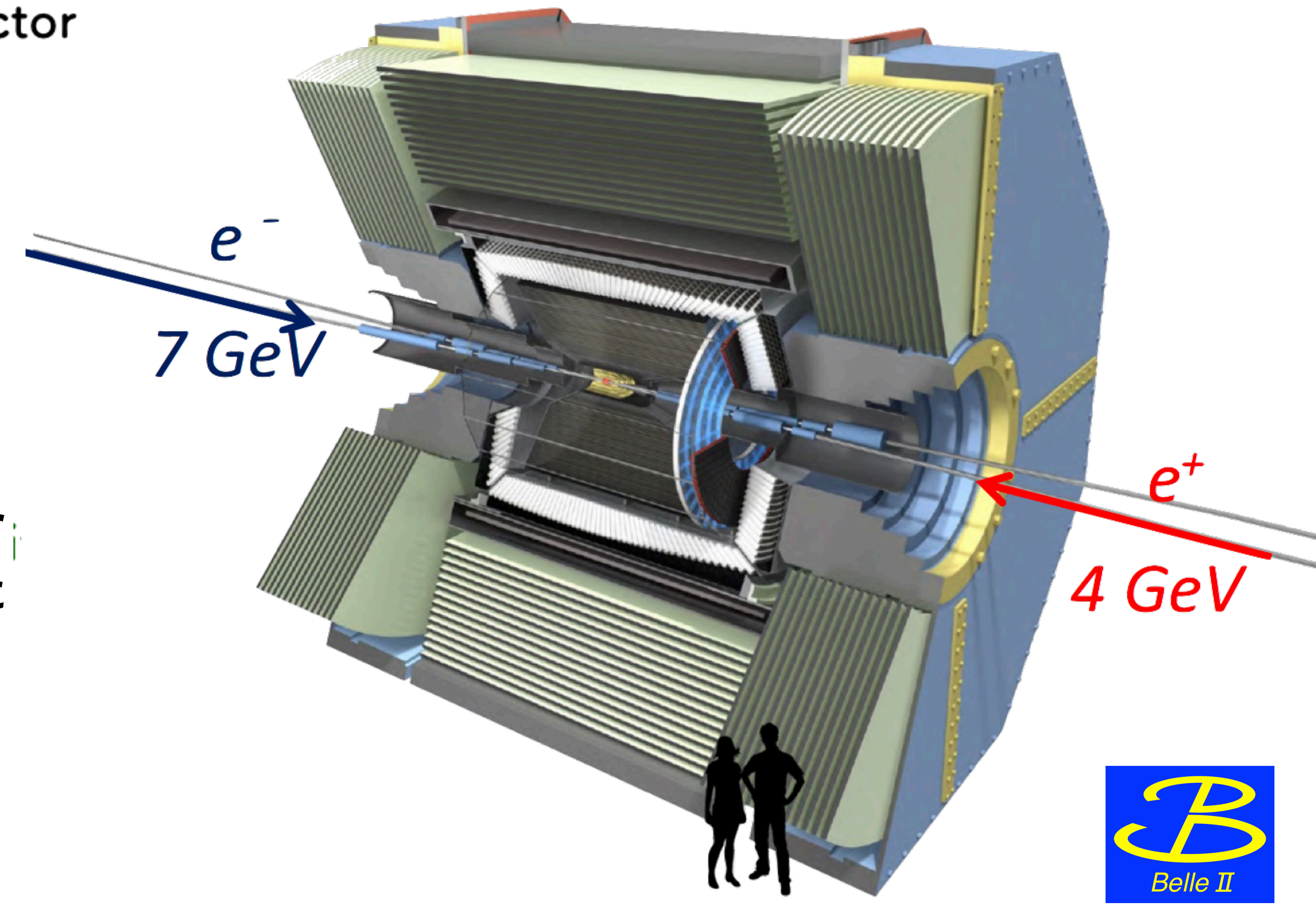
$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1}$$

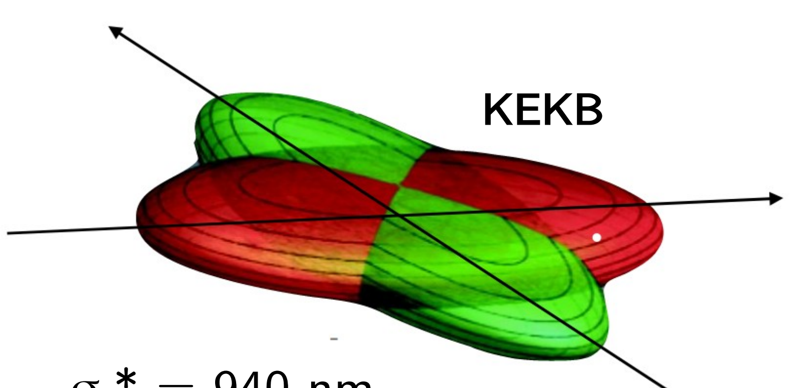
The next Luminosity Frontier



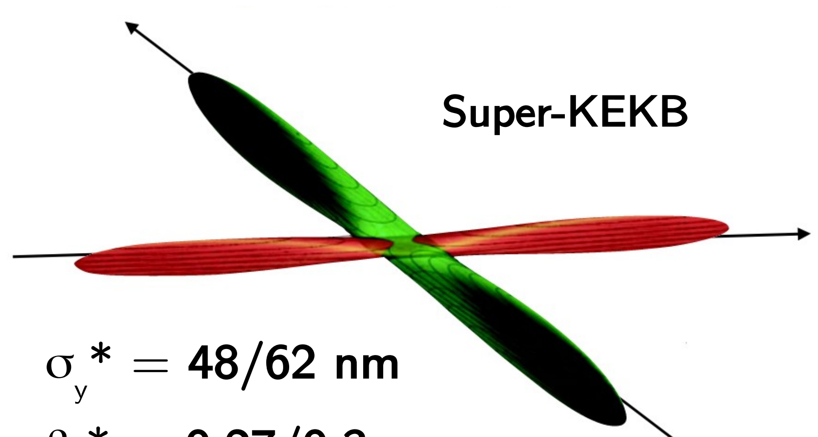
SuperKEKB $e^- \xrightarrow{7\ \mathrm{GeV}} (\star) \xleftarrow{4\ \mathrm{GeV}} e^+$ Belle II







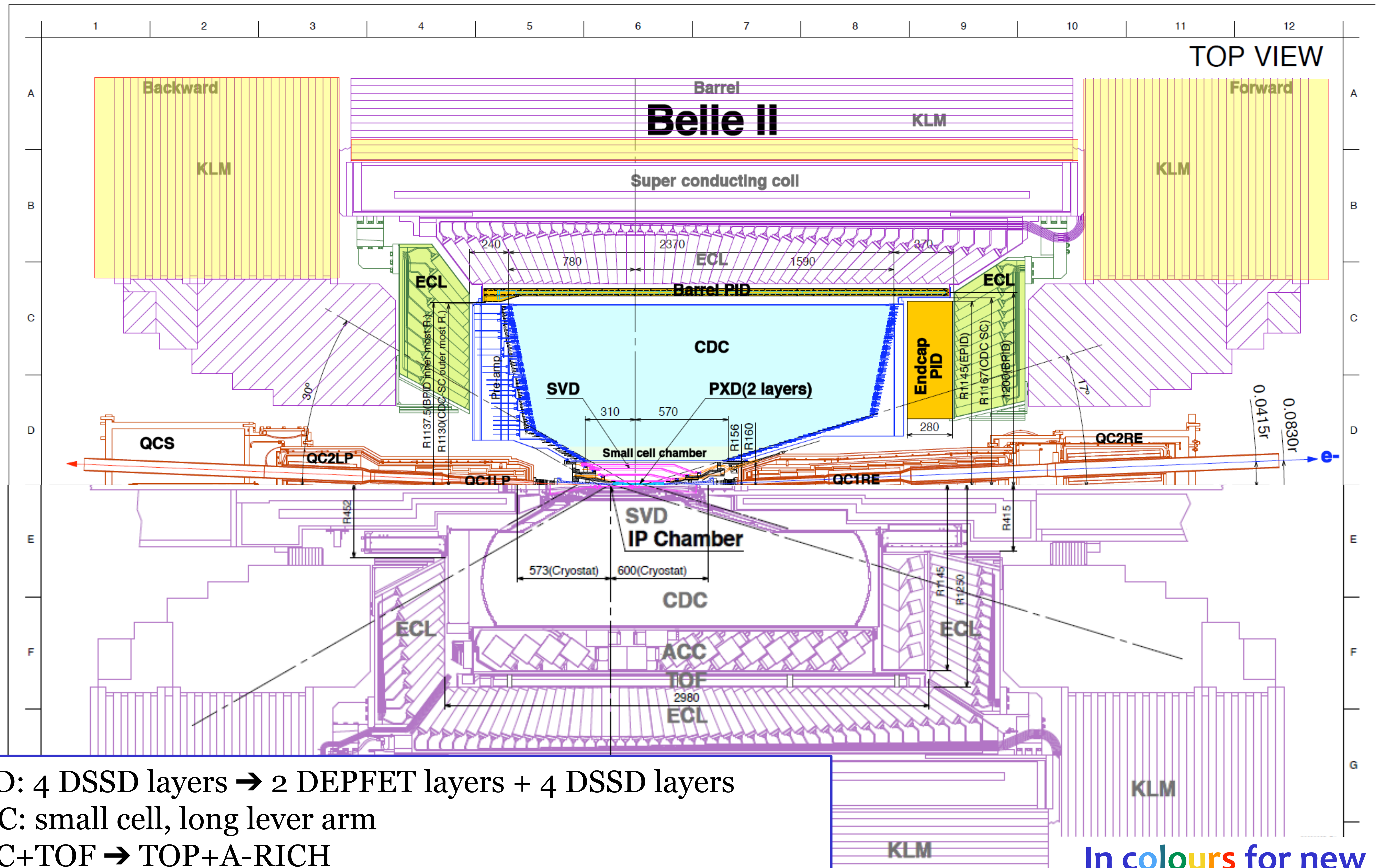
$\sigma_y^* = 940$ nm
$\beta_y^* = 5.9$ mm
$\sigma_x^* = 147/170$ μm



$\sigma_y^* = 48/62$ nm
$\beta_y^* = 0.27/0.3$ mm
$\sigma_x^* = 10.1/10.7$ μm

$$\mathcal{L}_{\mathrm{II}}^{\mathrm{peak}} \approx 30 \times \mathcal{L}_{\mathrm{I}}^{\mathrm{peak}}$$

$$\int^{\mathrm{goal}} \mathcal{L}_{\mathrm{II}}\, dt = 50\ \mathrm{ab}^{-1} \approx 50 \int \mathcal{L}_{\mathrm{I}}\, dt$$



SVD: 4 DSSD layers ➔ 2 DEPFET layers + 4 DSSD layers
CDC: small cell, long lever arm
ACC+TOF ➔ TOP+A-RICH
ECL: waveform sampling
KLM: RPC ➔ Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours for new components

The Belle II Collaboration

26 countries/regions, ~120 institutions, ~1000 collaborators

Belle II

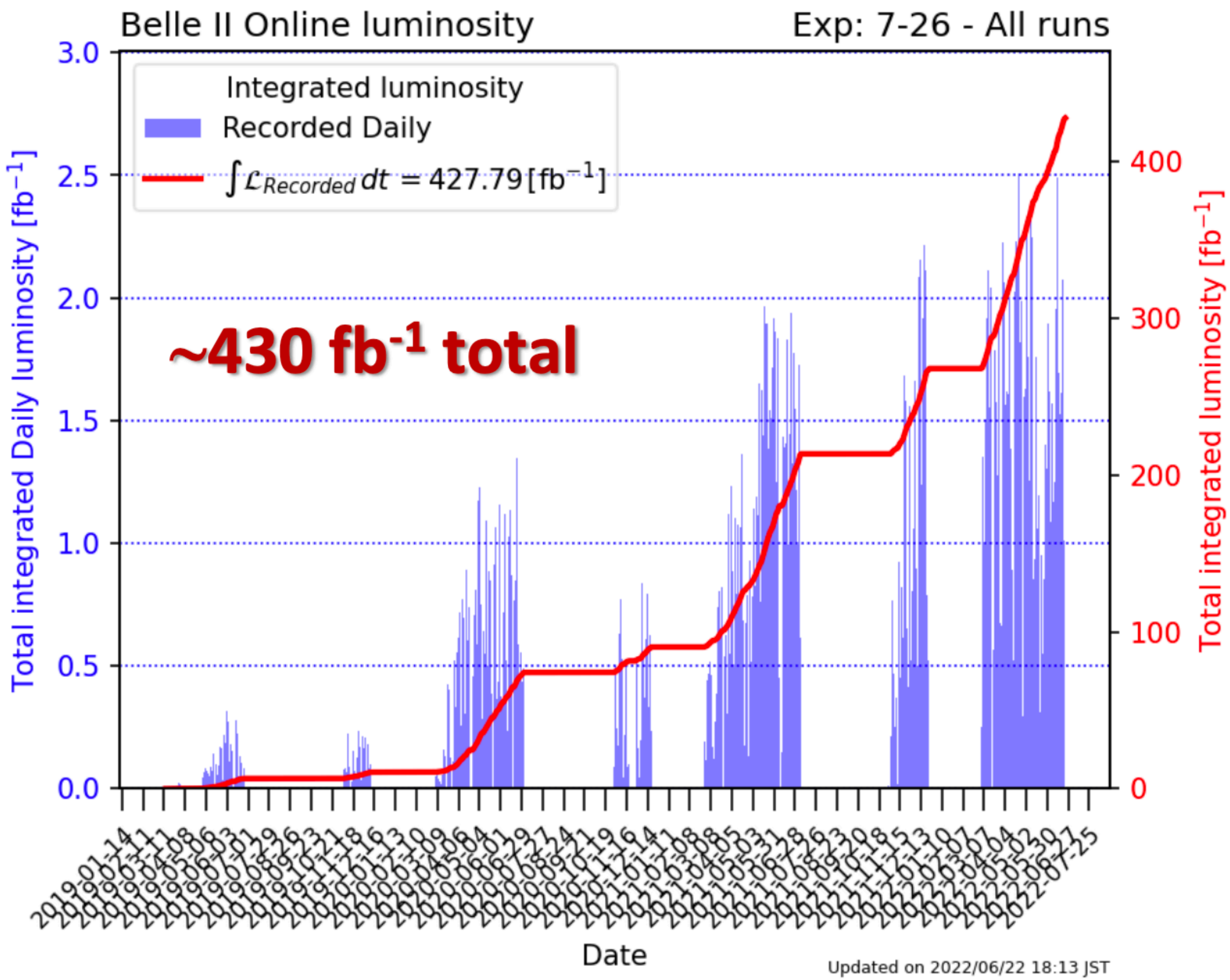
Collected luminosity before LS1 (2019-2022)2

Belle II has been in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy.

(*See next slide!*)

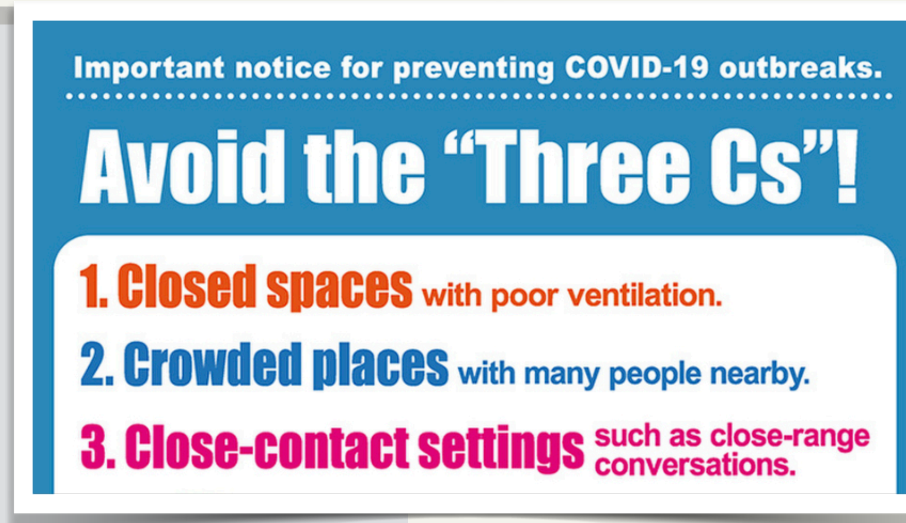
peak luminosity world record

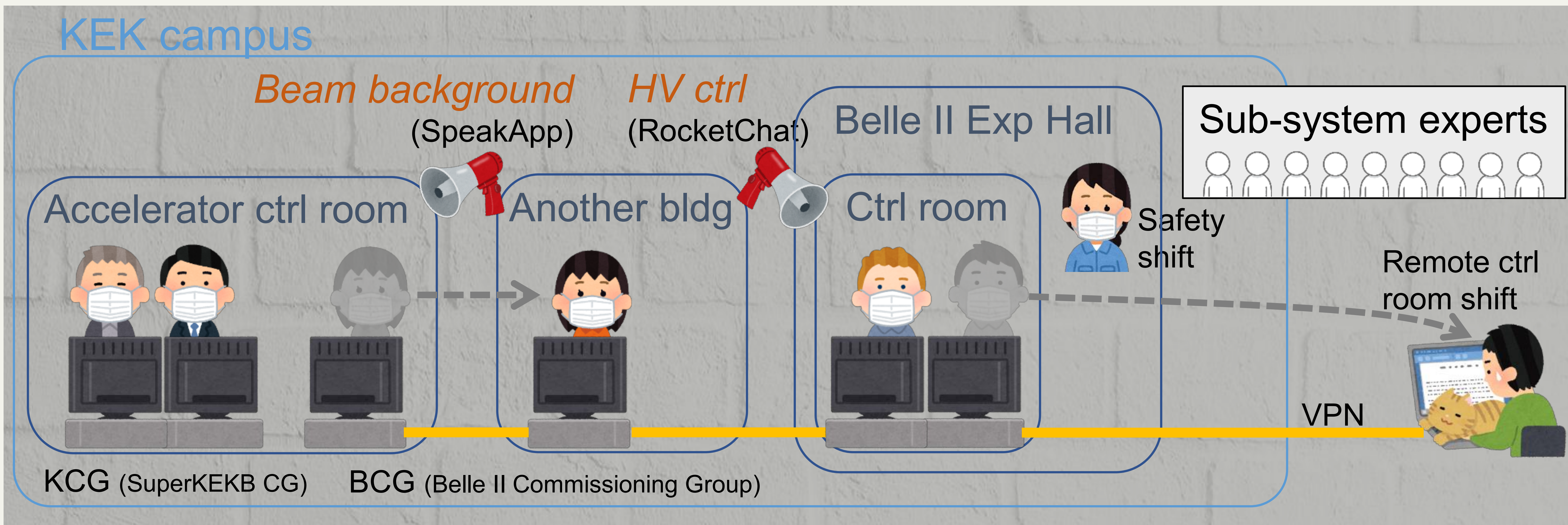
$4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$



Belle II operation status under Pandemic

- Minimize person-to-person contact, and avoid 3C
  - ✓ Remote control-room shifts and expert shifts
  - ✓ Travel restrictions (~40 Belle II colleagues on-site)
  - ✓ Online meetings





from ICHEP2020 talk by K. Matsuoka

Saga-Yonsei Joint Workshop X | Belle II | Belle II Luminosity - Belle II - D | Index of Belle publication # 63

https://yhep-indico.yonsei.ac.kr/event/497/timetable/

Wednesday, 18 January

10:00 → 11:45 **Lecture: Lecture 3 (mini-lecture & seminars)**

Convener: Prof. Takahiro Fusayasu (Saga Univ.)

10:00 **Introduction to Belle (II) and recent physics highlights** — 35m

Speaker: Prof. Youngjoon Kwon (Yonsei Univ.)

10:35 **B --> rho gamma and other EWP from Belle & Belle II** — 35m

Speaker: Dr Shun Watanuki (Yonsei University)

11:10 **Physics of quarkonia at Belle (II)** — 35m

Speaker: Dr Junhao Yin (Korea Univ.)

11:45 → 14:00 **Lunch** — 2h 15m

14:00 → 16:00 **Lecture: Lecture 4 & a seminar**

Convener: Youngjoon Kwon (Yonsei Univ.)

14:00 **Introduction to the ALICE experiment and its detector** — 1h 30m

Speaker: Prof. Takahiro Fusayasu (Saga University)

15:30 **Atmospheric axionlike particles at Super-Kamiokande** — 30m

Speaker: Prof. Po-Yen Tseng (National Tsing Hua University)

slide.pdf

Belle II Physics Mind-map

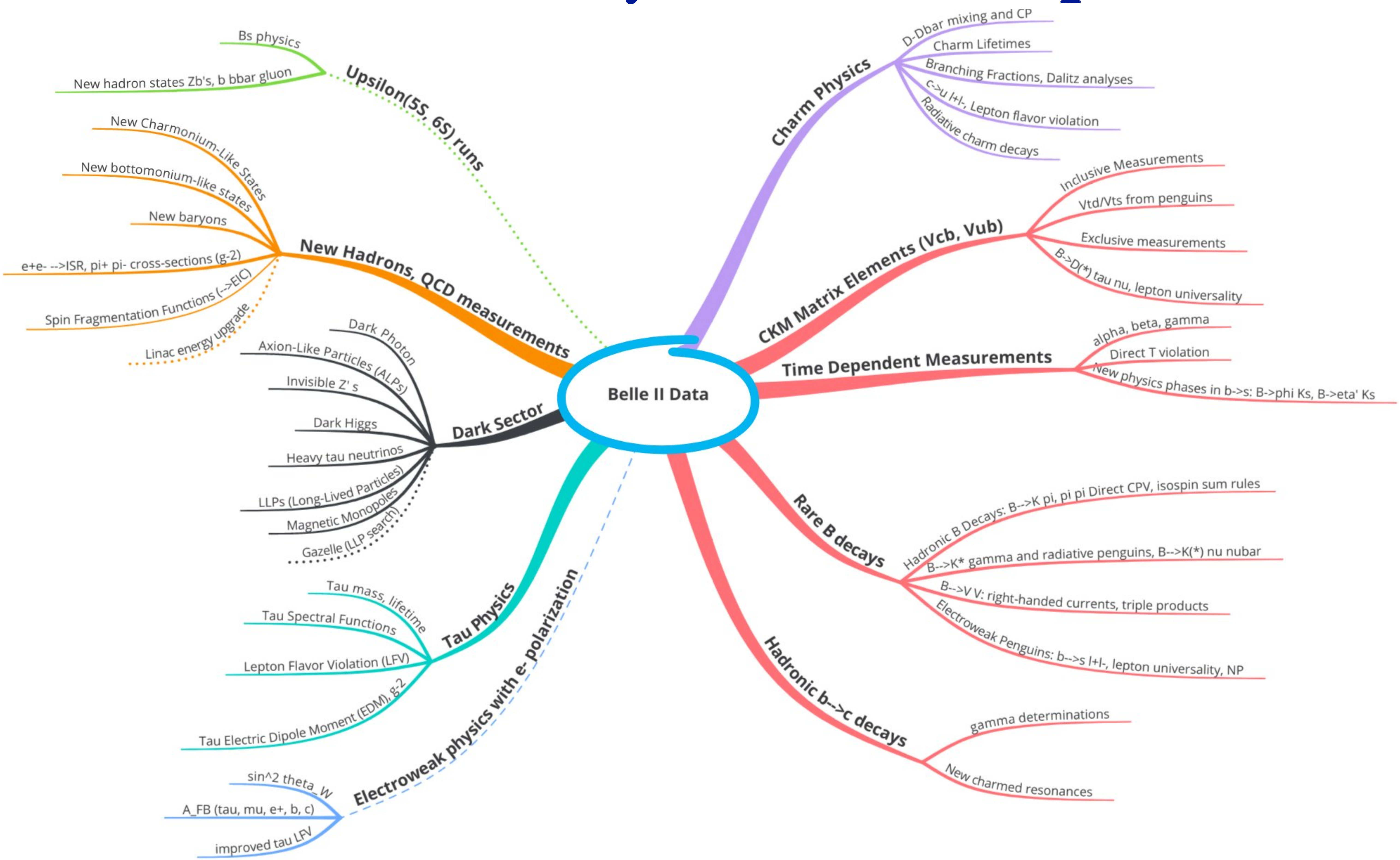
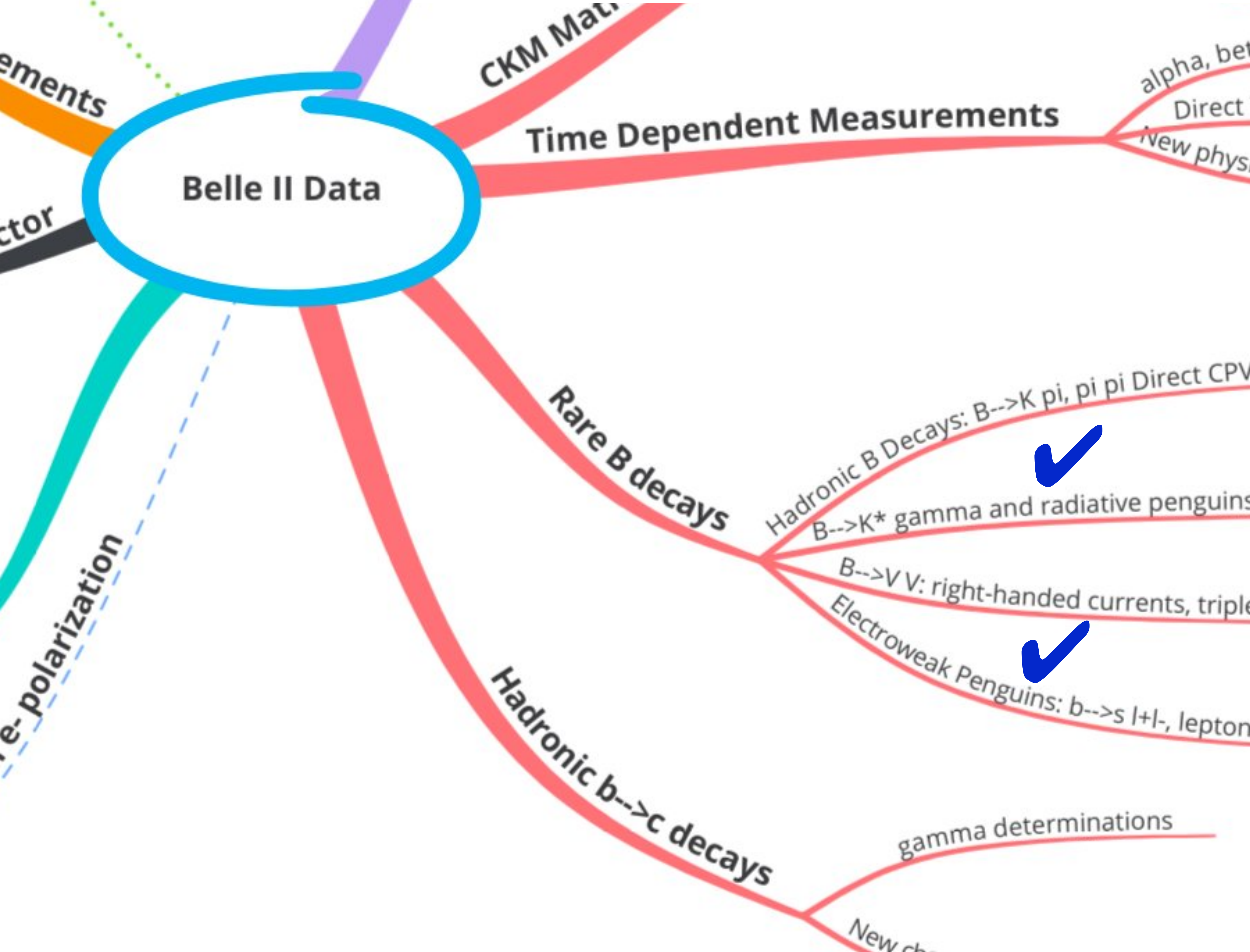


Image courtesy of Tom Browder

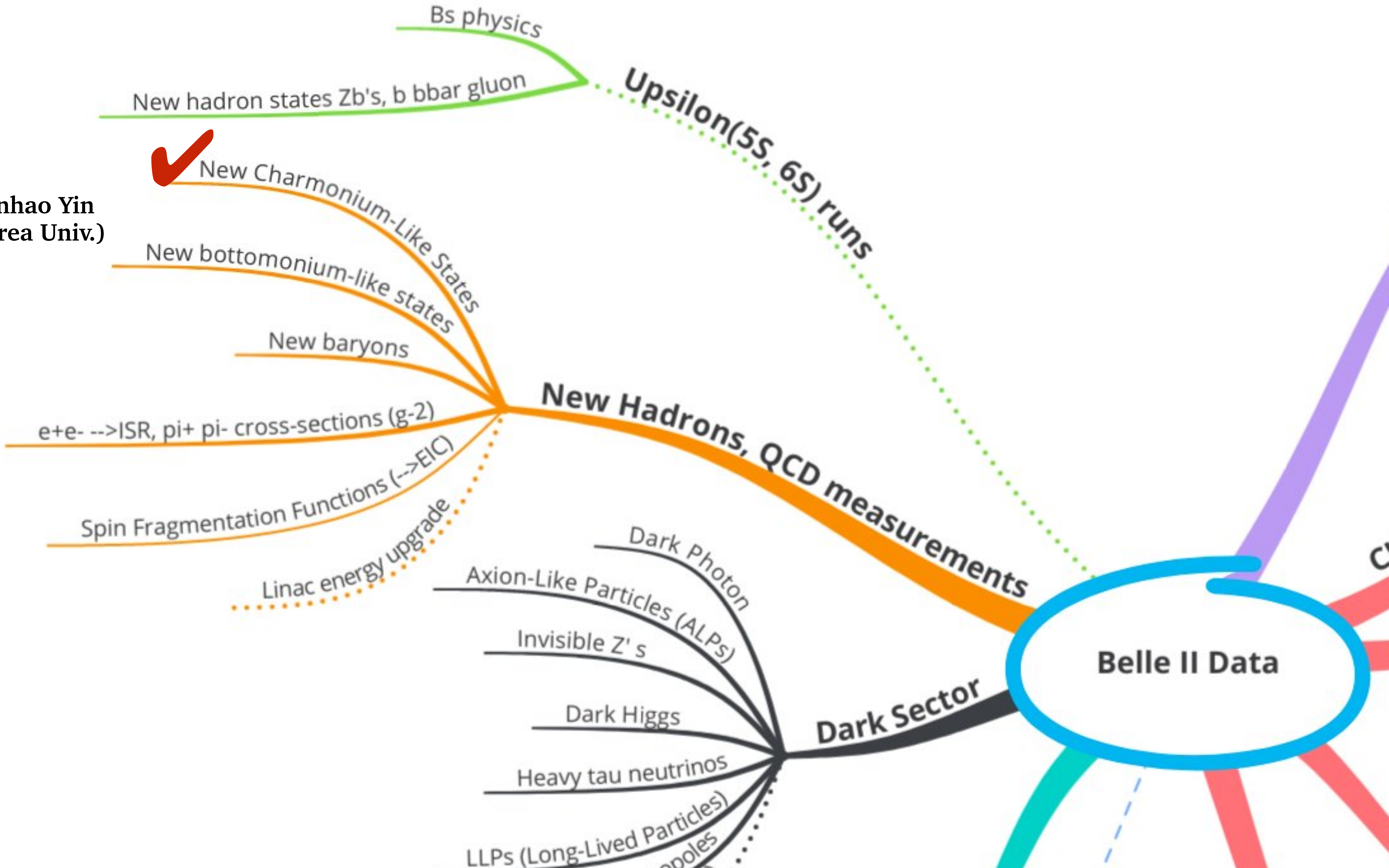
Belle II Physics Mind-map



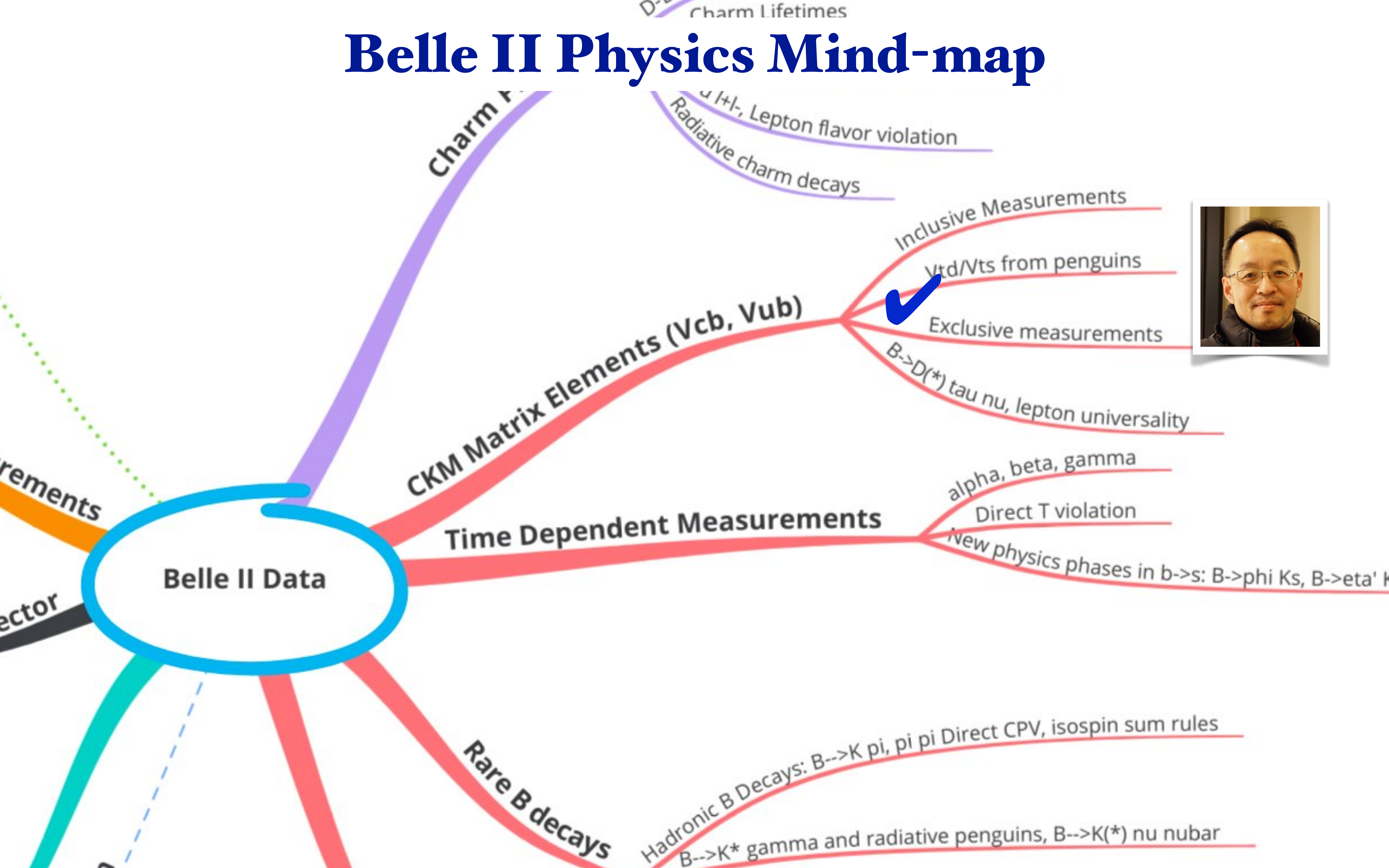
Shun Watanuki
(Yonsei HEP)

Belle II Physics Mind-map

Junhao Yin
(Korea Univ.)



Belle II Physics Mind-map



Belle Preprint 2022-34, KEK Preprint 2022-47

Measurement of Differential Distributions of $B \to D^* \ell \bar{\nu}_\ell$ and Implications on $|V_{cb}|$

M. T. Prim, F. Bernlochner, F. Metzner, K. Lieret, T. Kuhr, I. Adachi, H. Aihara, S. Al Said, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, R. Ayad, V. Babu, S. Bahinipati, Sw. Banerjee, M. Bauer, P. Behera, J. Bennett, M. Bessner, V. Bhardwaj, B. Bhuyan, T. Bilka, D. Biswas, D. Bodrov, J. Borah, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, A. Budano, M. Campajola, L. Cao, D. Červenkov, M.-C. Chang, V. Chekelian, B. G. Cheon, K. Chilikin, H. E. Cho, K. Cho, Y. Choi, S. Choudhury, D. Cinabro, S. Das, N. Dash, G. de Marino, G. De Nardo, G. De Pietro, R. Dhamija, F. Di Capua, J. Dingfelder, Z. Doležal, T. V. Dong, D. Epifanov, T. Ferber, D. Ferlewicz, A. Frey, B. G. Fulsom, V. Gaur, A. Garmash, A. Giri, P. Goldenzweig, E. Graziani, T. Gu, K. Gudkova, C. Hadjivasiliou, S. Halder, T. Hara, K. Hayasaka, H. Hayashii, M. T. Hedges, D. Herrmann, M. Hernández Villanueva, C.-L. Hsu, T. Iijima, K. Inami, G. Inguglia, N. Ipsita, A. Ishikawa, R. Itoh, M. Iwasaki, W. W. Jacobs, E.-J. Jang, S. Jia, Y. Jin, K. K. Joo, A. B. Kaliyar, K. H. Kang, T. Kawasaki, C. Kiesling, C. H. Kim, D. Y. Kim, K.-H. Kim, Y.-K. Kim, K. Kinoshita, P. Kodyš, T. Konno, A. Korobov, S. Korpar, E. Kovalenko, P. Križan, P. Krokovny, M. Kumar, R. Kumar, K. Kumara, A. Kuzmin, Y.-J. Kwon, K. Lalwani, J. S. Lange, M. Laurenza, S. C. Lee, P. Lewis, J. Li, L. K. Li, Y. Li, J. Libby, Y.-R. Lin, D. Liventsev, T. Luo, M. Masuda, T. Matsuda, D. Matvienko, S. K. Maurya, F. Meier, M. Merola, K. Miyabayashi, R. Mizuk, G. B. Mohanty, I. Nakamura, M. Nakao, Z. Natkaniec, A. Natochii, L. Nayak, N. K. Nisar, S. Nishida, K. Ogawa, S. Ogawa, H. Ono, P. Oskin, P. Pakhlov, G. Pakhlova, T. Pang, S. Pardi, H. Park, J. Park, S.-H. Park, A. Passeri, S. Paul, T. K. Pedlar, R. Pestotnik, L. E. Piilonen, T. Podobnik, E. Prencipe, A. Rabusov, M. Röhrken, A. Rostomyan, N. Rout, G. Russo, S. Sandilya, A. Sangal, L. Santelj, V. Savinov, G. Schnell, C. Schwanda, A. J. Schwartz, Y. Seino, K. Senyo, M. E. Sevior, W. Shan, M. Shapkin, C. Sharma, J.-G. Shiu, B. Shwartz, F. Simon, A. Soffer, A. Sokolov, E. Solovieva, M. Starič, M. Sumihama, T. Sumiyoshi, M. Takizawa, U. Tamponi, K. Tanida, F. Tenchini, K. Trabelsi, T. Uglov, Y. Unno, S. Uno, P. Urquijo, Y. Usov, S. E. Vahsen, B. van Tonder, G. Varner, K. E. Varvell, A. Vinokurova, A. Vossen, E. Waheed, D. Wang,

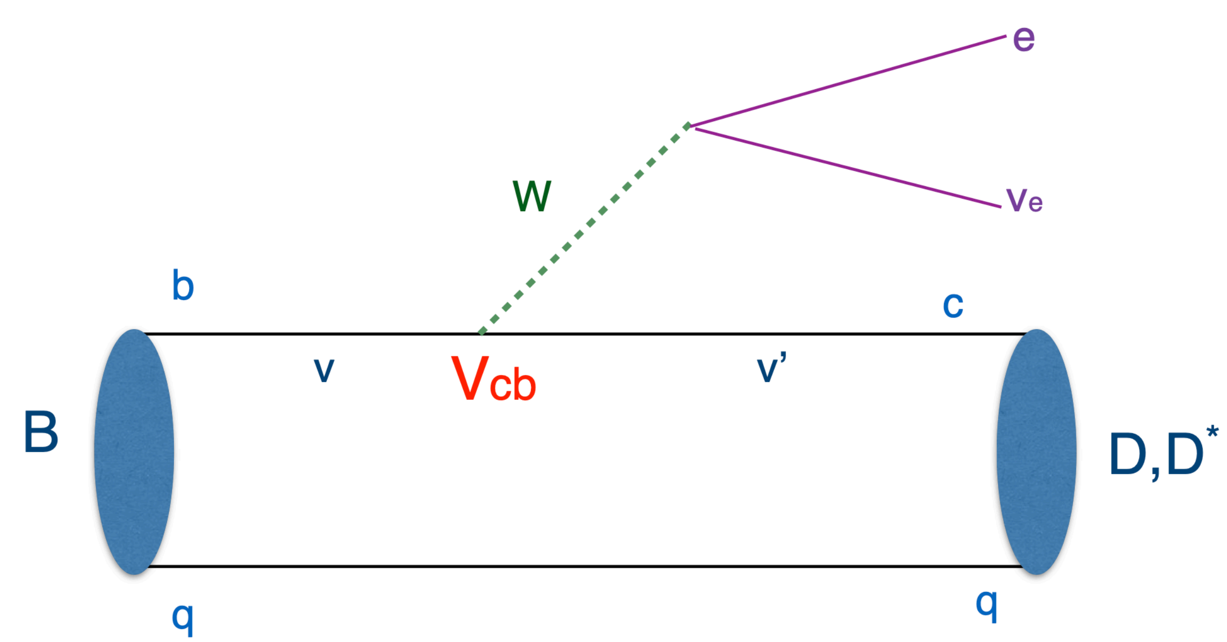
Belle Preprint 2022-34, KEK Preprint 2022-47

Measurement of Differential Distributions of $B \to D^{*}\ell\bar{\nu}_{\ell}$ and Implications on $|V_{cb}|$

M. T. Prin ... Al Said,
D. M. Asne ... Banerjee,
M. Bau ... iswas,
D. Bodrov ... ampajola,
L. C ... ho,
K. Ch ... ardo,
G. De ... anov,
T. Ferbe ... nzweig,
E. Grazia ... ayashii,
M. T. He ... nguglia,
N. Ipsita ... K. Joo,
A. B. Kaliy ... -K. Kim,
K. Kinosh ... rokovny,
M. Kumar ... aurenza,
S. C. Lee ... Masuda,
T. Ma ... zuk,
G. B. ... isar,
S. Nishida ... S. Pardi,
H. Par ... lonen,
T. Podobn ... Sandilya,
A. Sang ... Senyo,
M. E. S ... Soffer,
A. Sok ... poni,
K. Tanida, F. Tenchini, K. Trabelsi, T. Uglov, Y. Unno, S. Uno, P. Urquijo, Y. Usov, S. E. Vahsen,
R. van Tonder, G. Varner, K. E. Varvell, A. Vinokurova, A. Vossen, E. Waheed, D. Wang

$$B \to D^{*}\ell\bar{\nu}_{\ell}$$

- Heavy-quark symmetry allows us to extract the CKM matrix element $|V_{cb}|$ with controlled theoretical uncertainties



clever use of heavy-quark symmetries
allows us to calculate the decay rates
at the special kinematic point of maximum momentum transfer to the leptons (v=v')
("zero recoil" point)

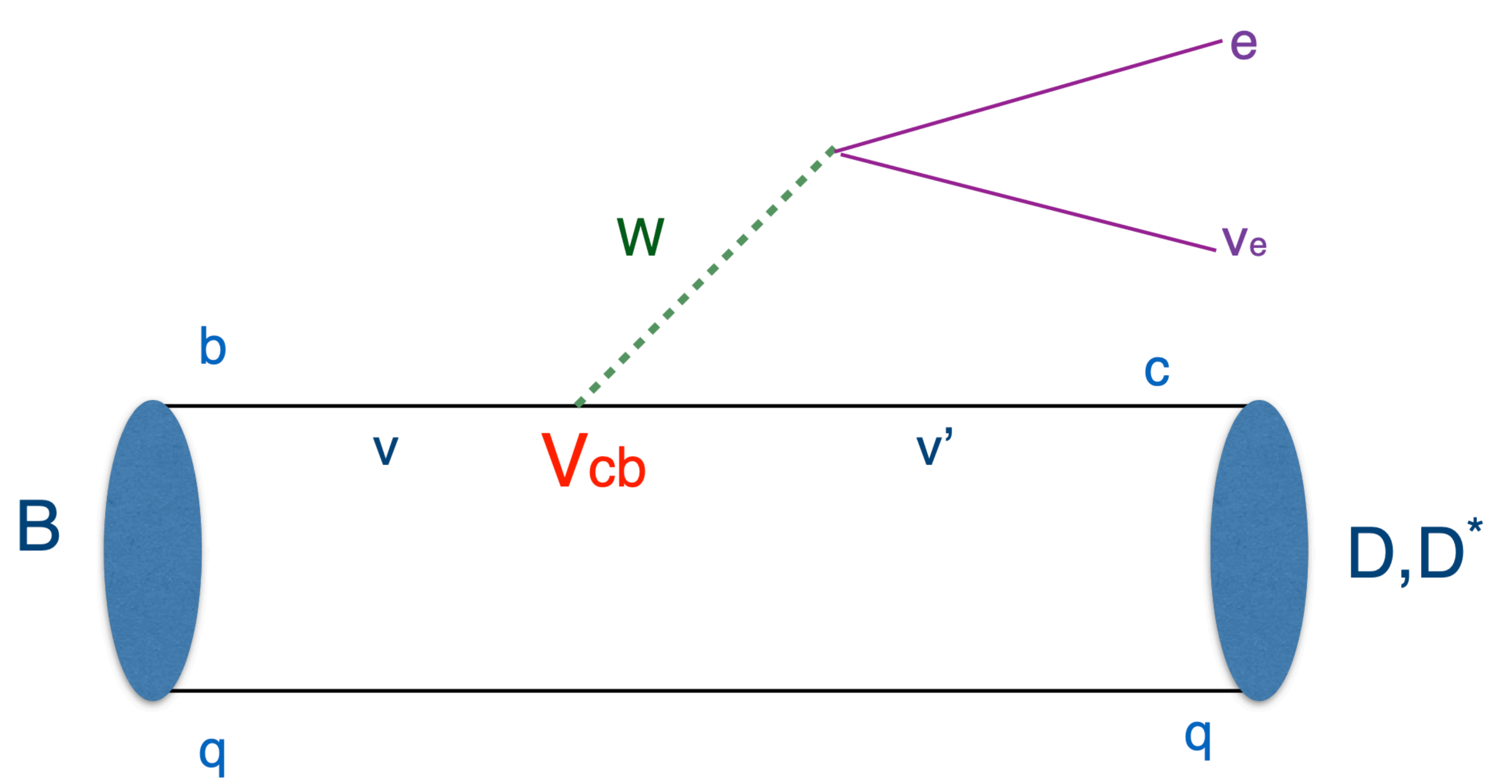
- How to deal with confinement effects in this hadronic process?

from Prof. S.J. Lee lecture @ SY XIX

Exclusive Semileptonic B Decays: Form factor relations and extraction of $|V_{cb}|$

Form factor relations

- Heavy-quark symmetry allows us to extract the CKM matrix element $|V_{cb}|$ with controlled theoretical uncertainties

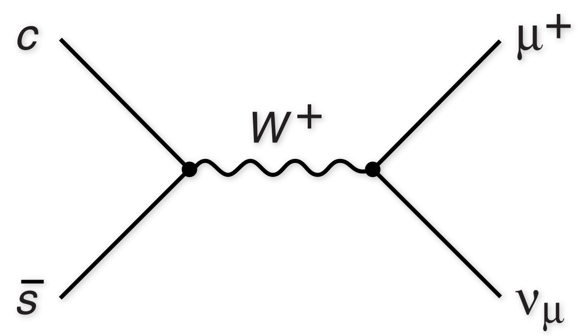


clever use of heavy-quark symmetries allows us to calculate the decay rates at the special kinematic point of maximum momentum transfer to the leptons (v=v')
("zero recoil" point)

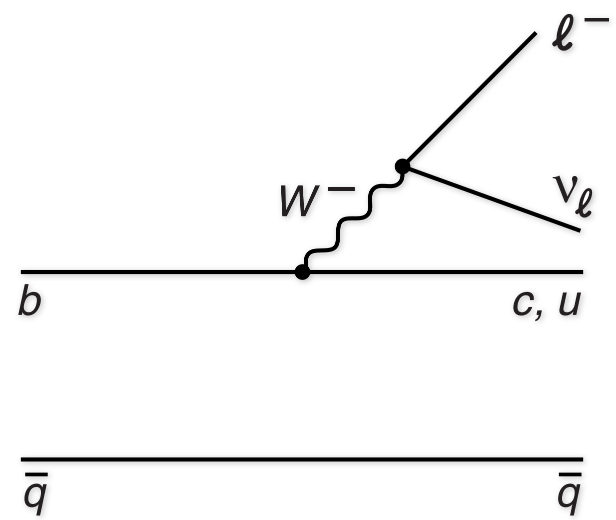
- How to deal with confinement effects in this hadronic process?

from Prof. S.J. Lee lecture @ SY XIX

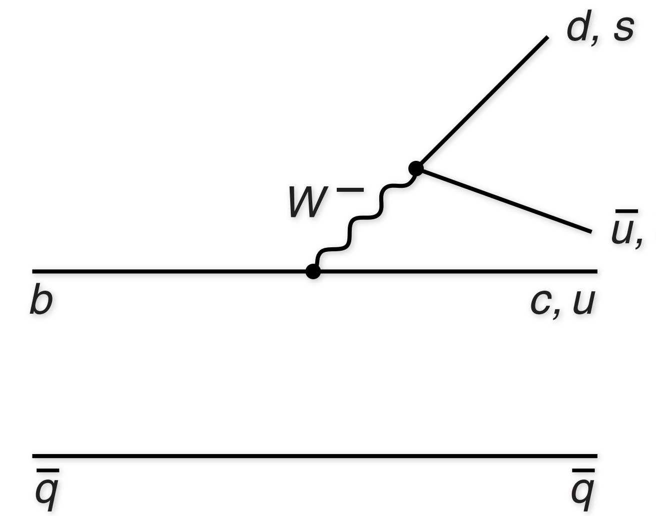
B-meson decays



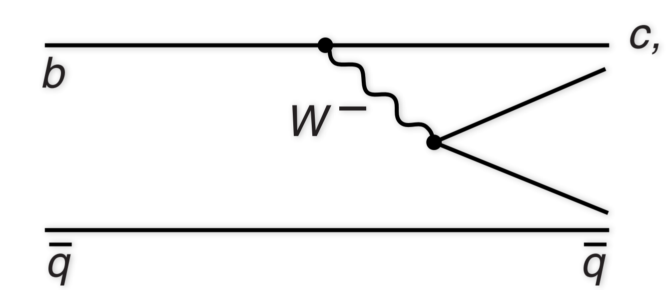
(a) Leptonic



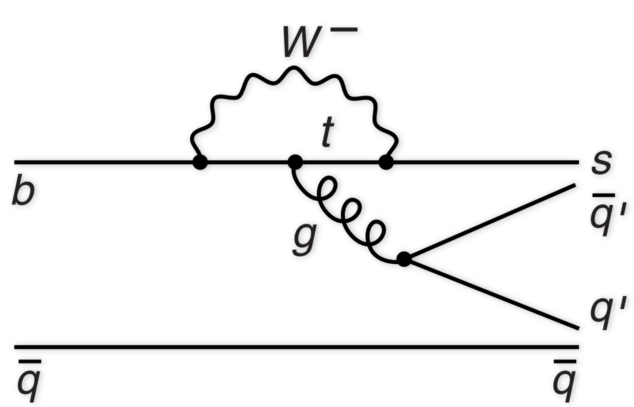
(b) Semileptonic



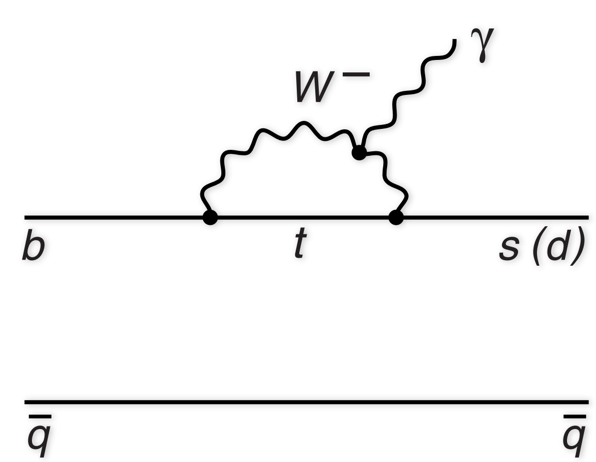
(c) Hadronic



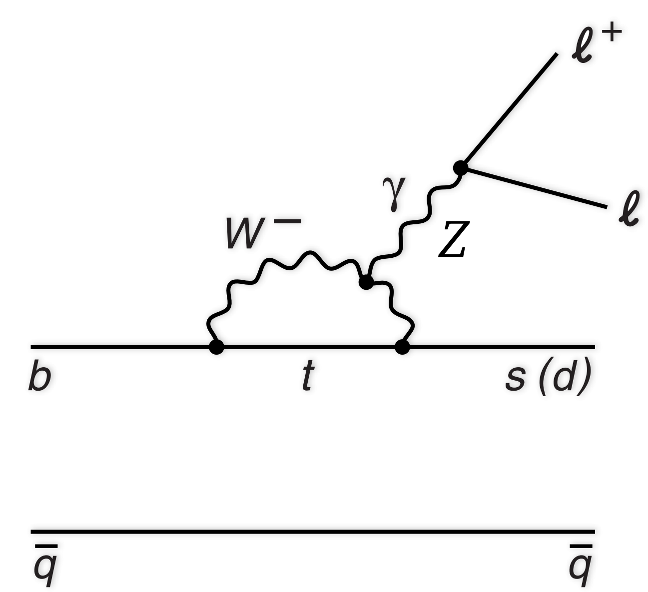
(d) Hadronic



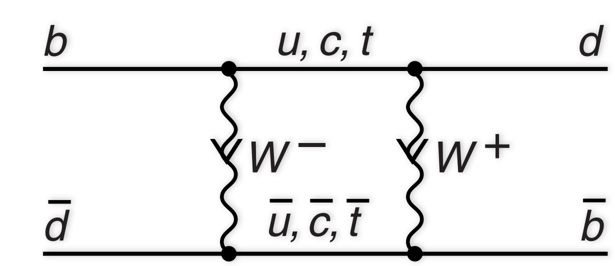
(e) Gluonic penguin



(f) EM penguin

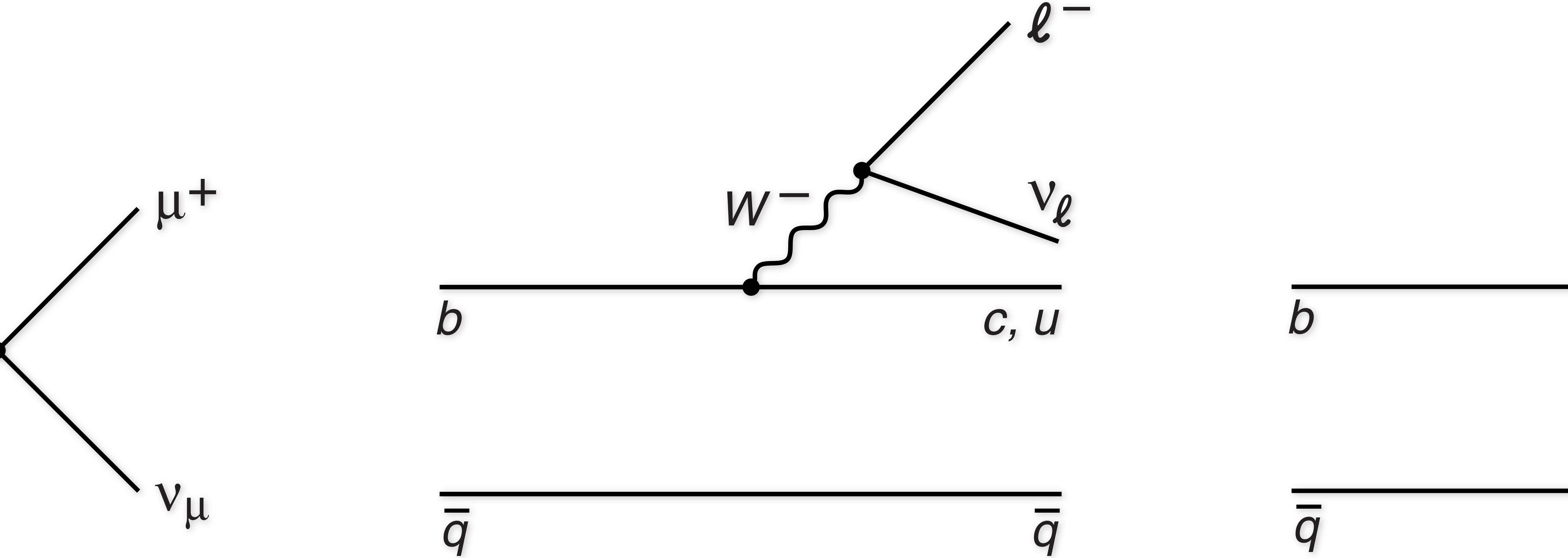


(g) EW penguin



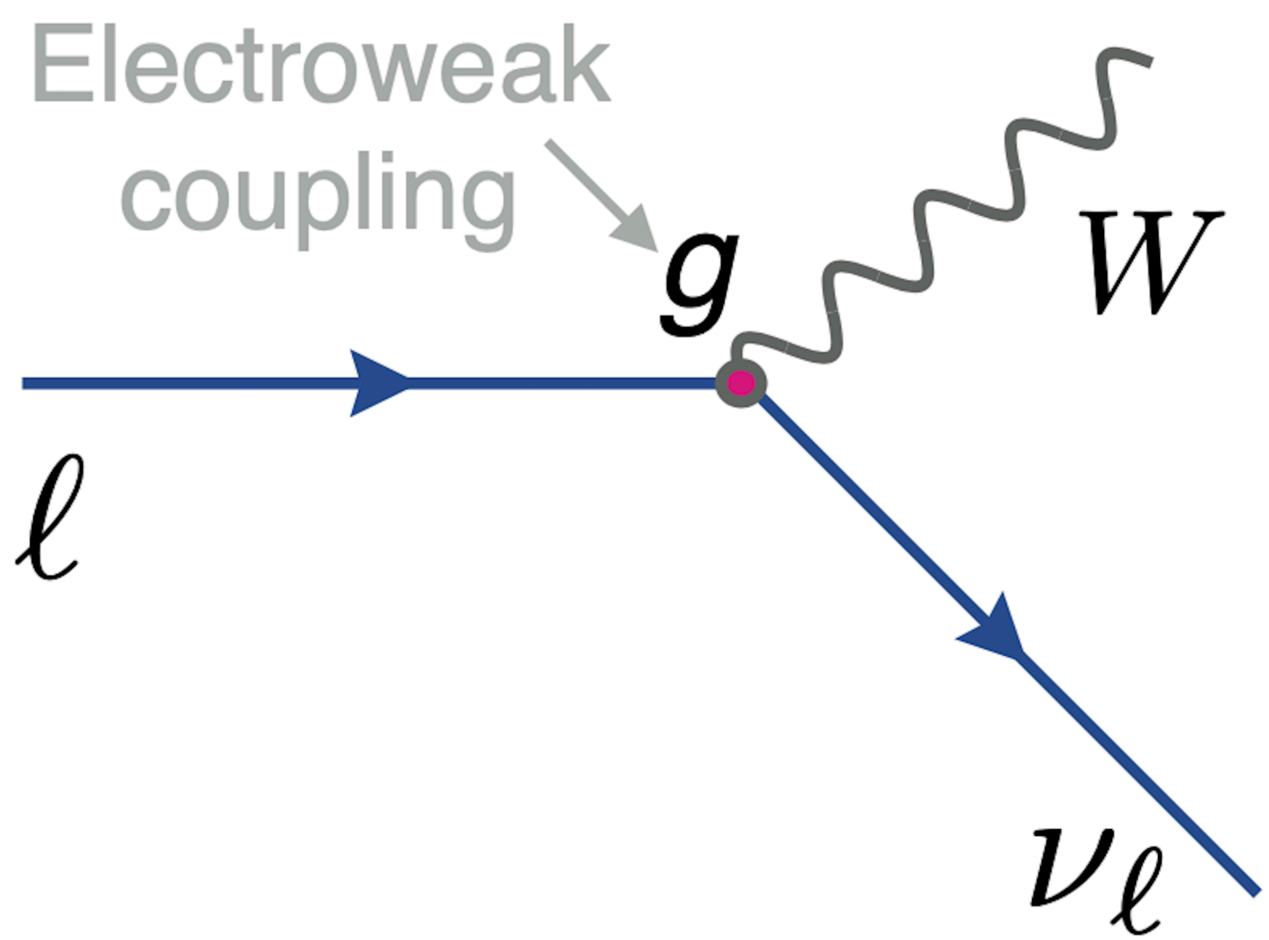
(h) oscillation

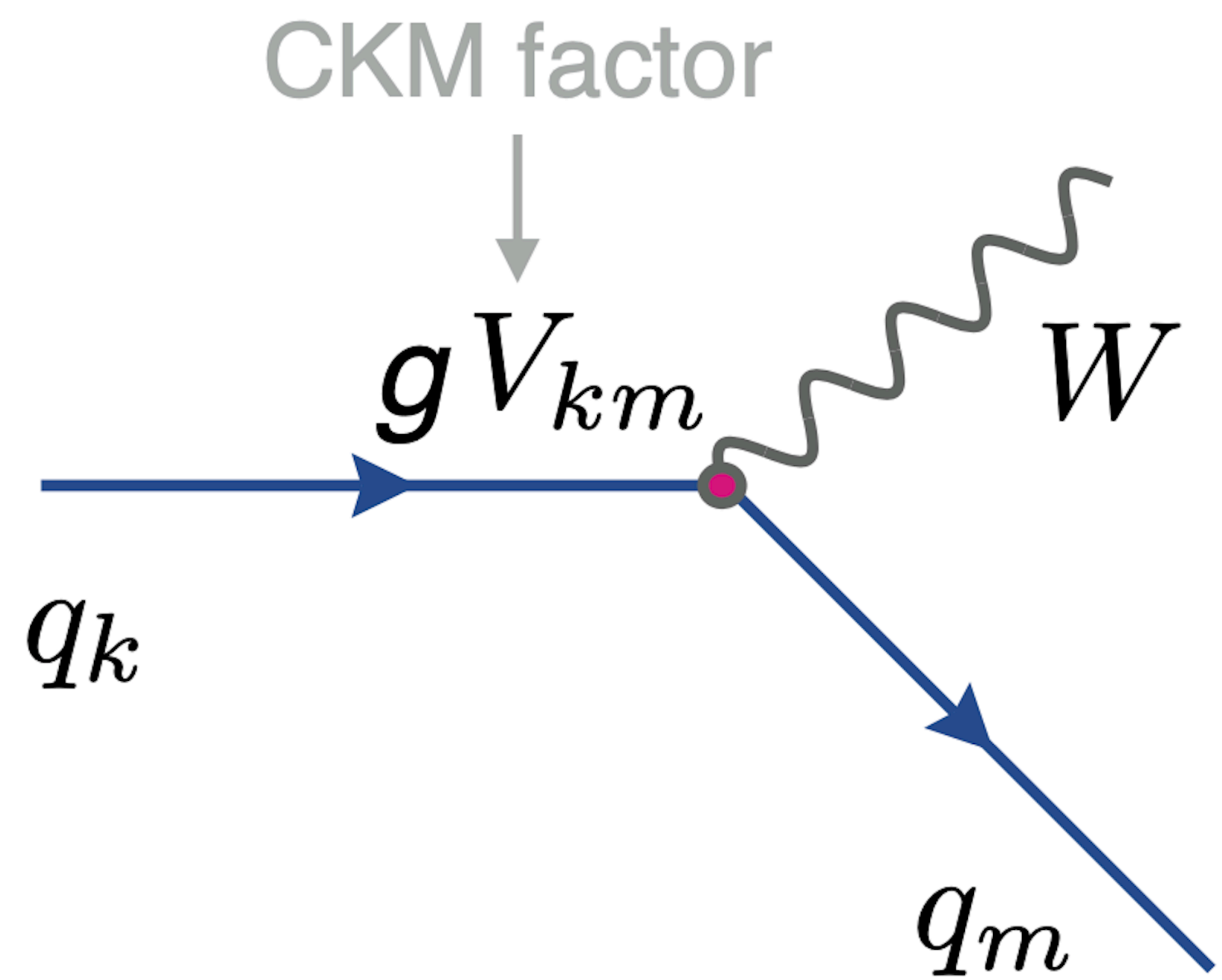
Semileptonic *B* decays



c (b) Semileptonic (c) H

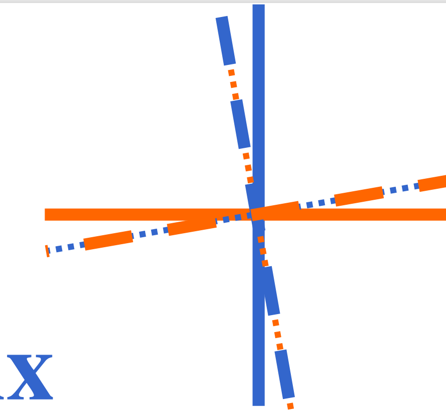
How fermions interact with $W^{\pm}$





Quark flavor mixing & CKM matrix

- For quarks,
  - weak interaction eigenstates ≠ mass eigenstates
  - mixing of quark flavors through a **unitary matrix**



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \left(V_{CKM}\right)\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

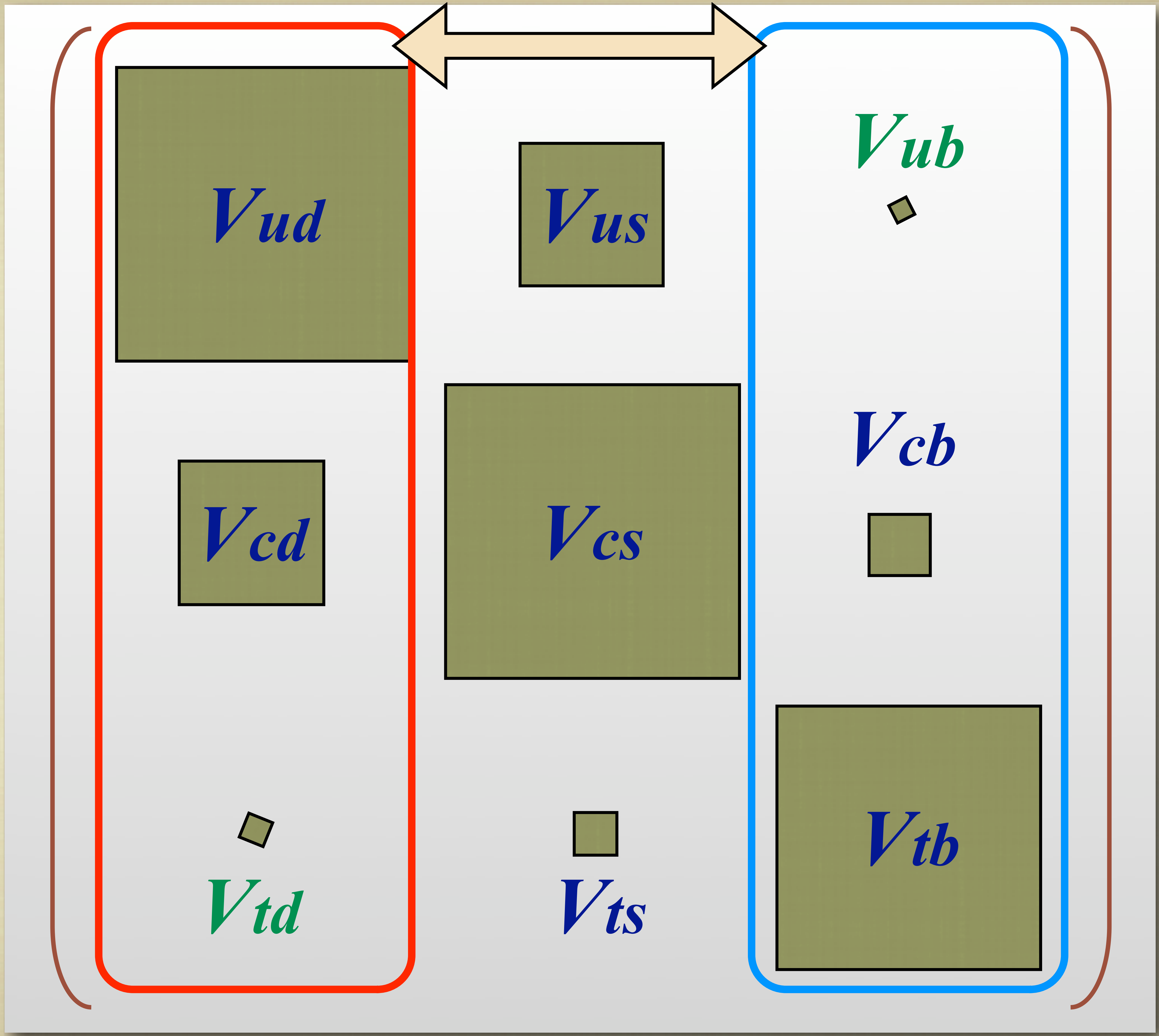
Wolfenstein parametrization

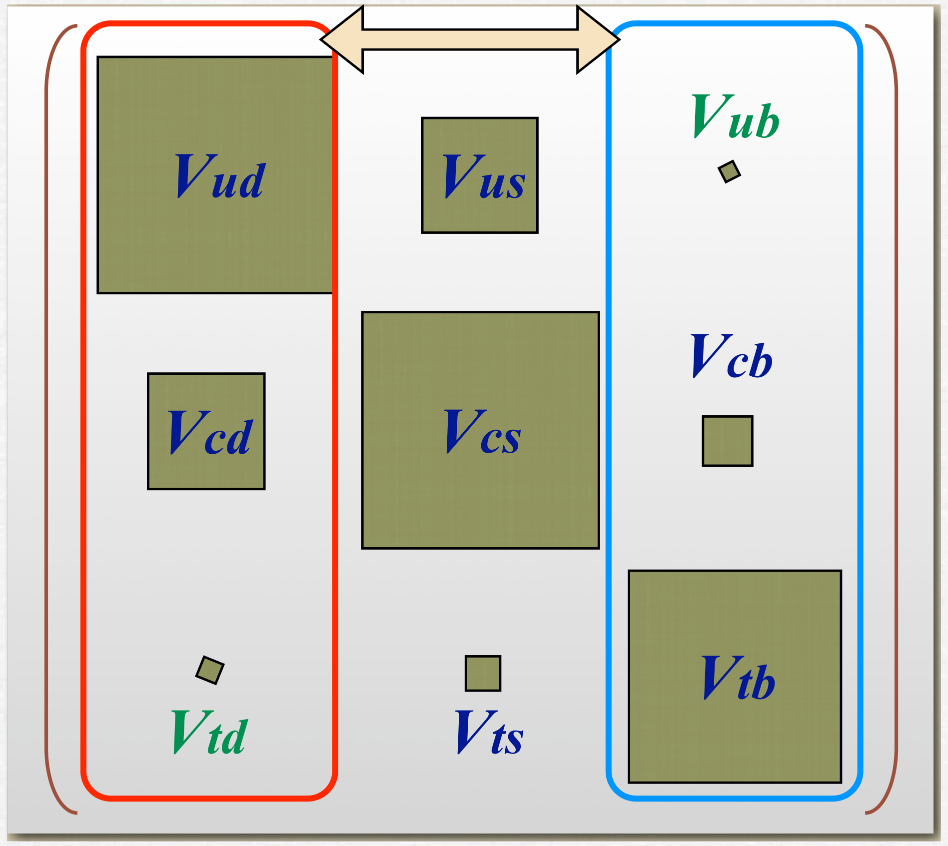
$$\mathbf{V}_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$|\lambda| \approx O(0.1)$

3 real parameters (λ, A, ρ) and 1 phase (η)

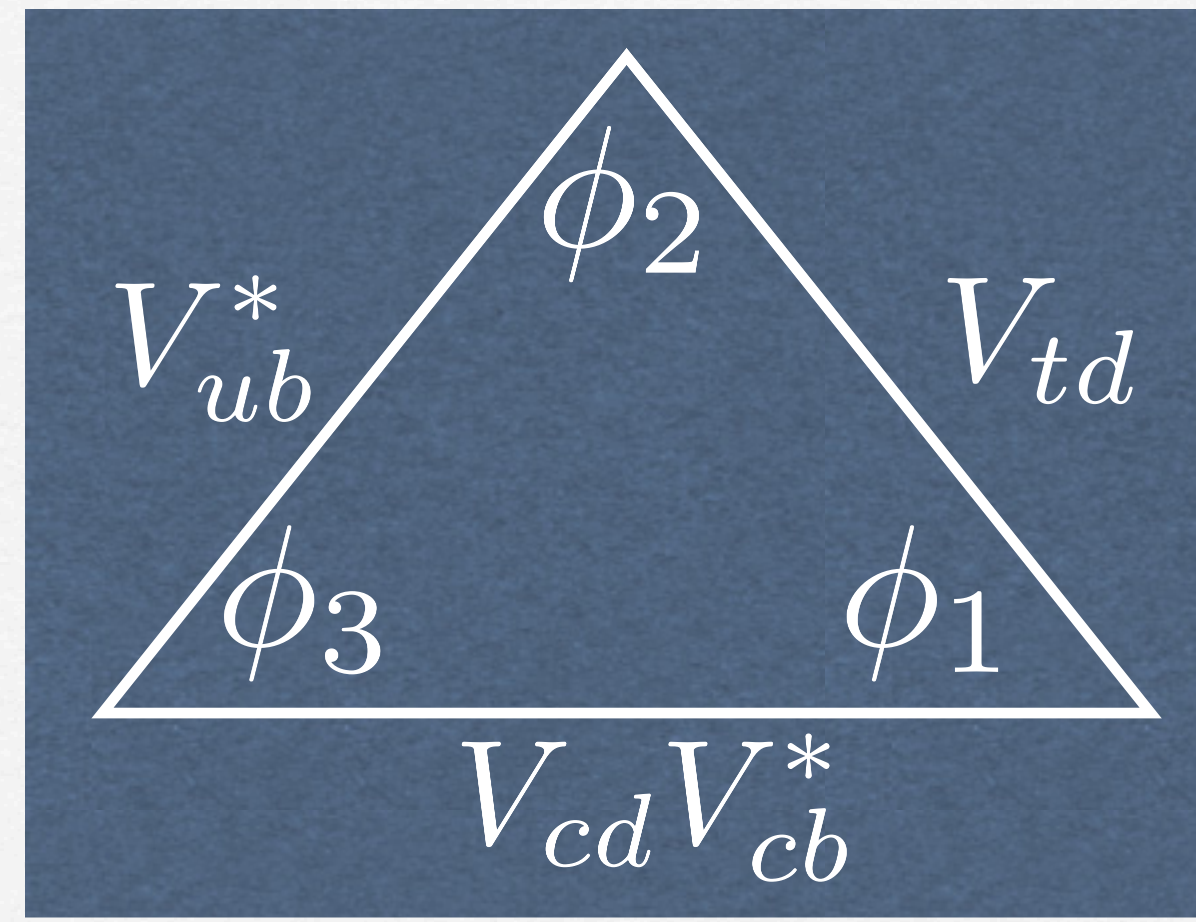
Test Unitarity?





$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

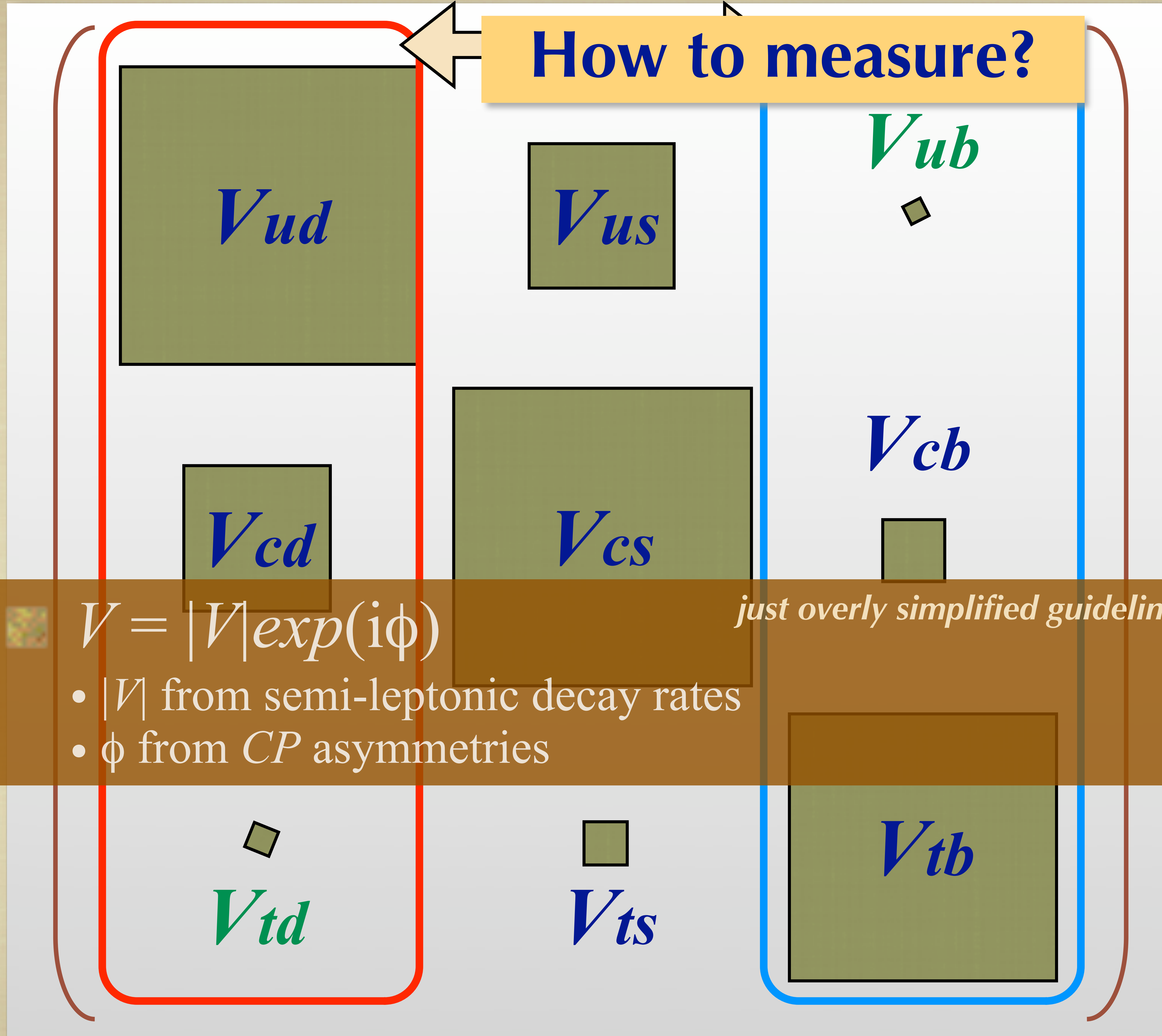
$$V_{ud} \cong V_{tb} \cong 1$$



Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
This talk:	易	難	魔

Z. Ligeti, from plenary talk @ ICHEP 2004

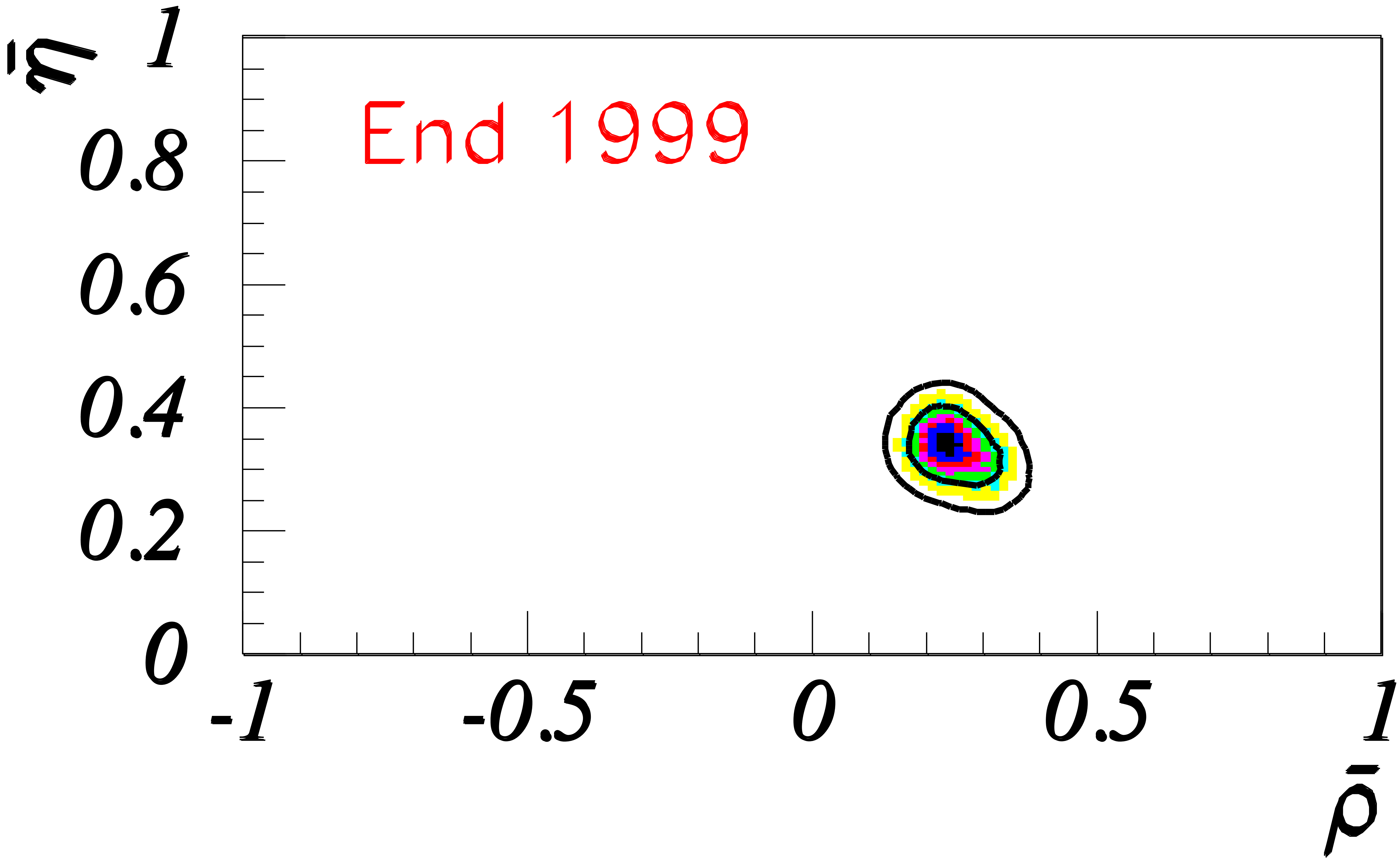
How to measure?



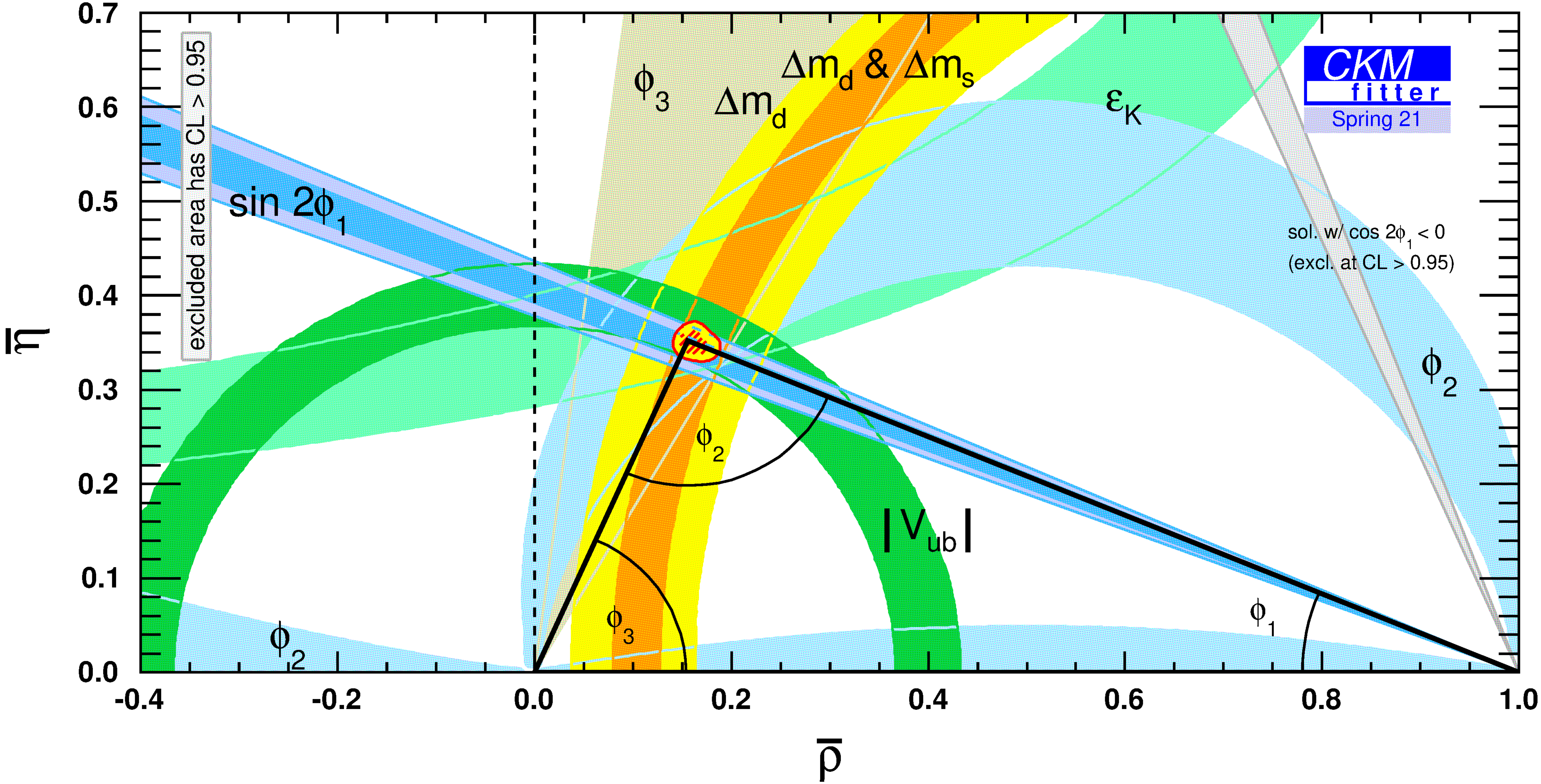
just overly simplified guidelines

$V = |V| exp(i\phi)$

- $|V|$ from semi-leptonic decay rates
- ϕ from *CP* asymmetries

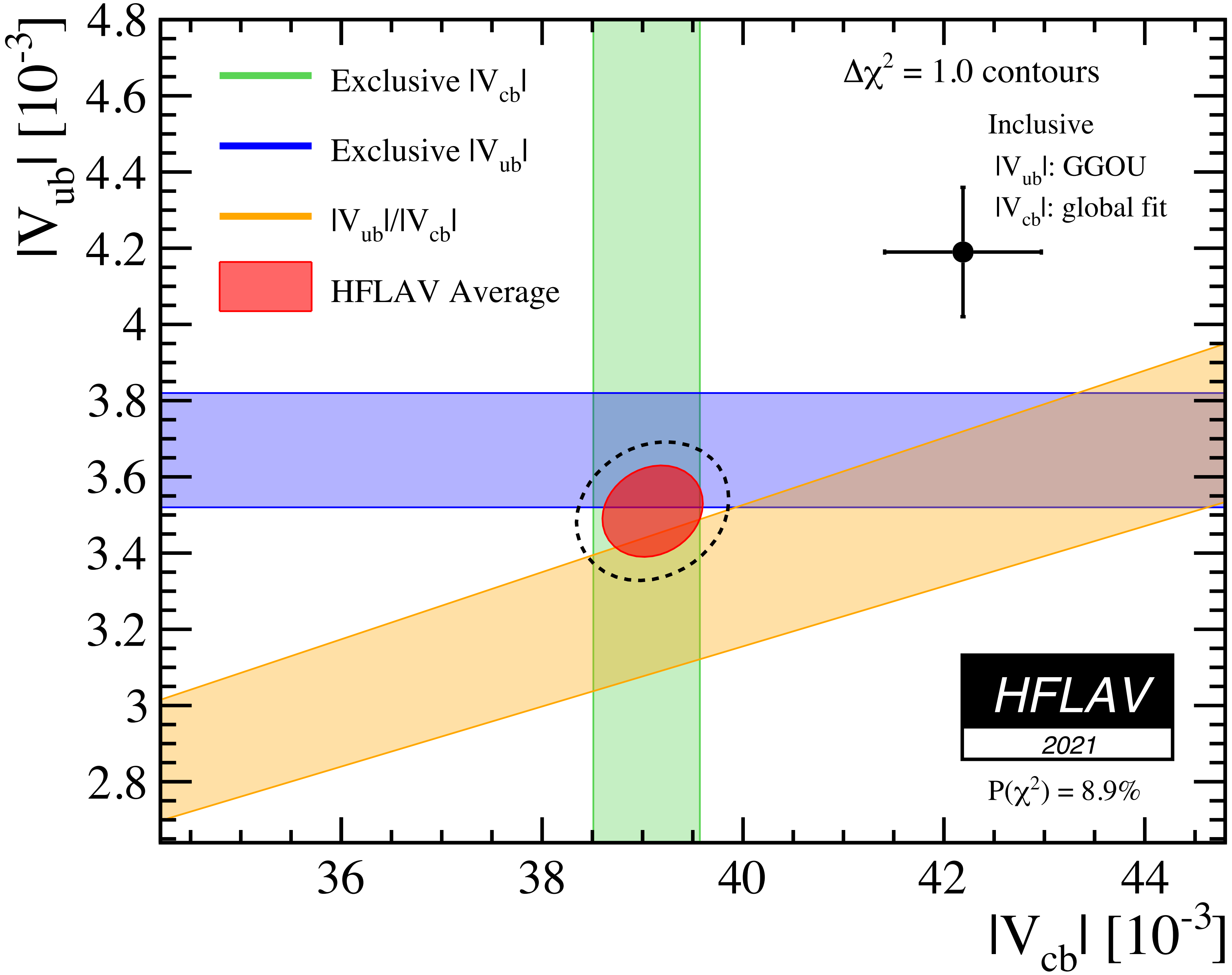

End 1999
$\bar{\eta}$
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
$\bar{\rho}$

CKM UT as of 2021



Inclusive vs. Exclusive Tension

in the measurements of $|V_{cb}|$, $|V_{ub}|$ between inclusive and exclusive approaches



$$|V_{ub}|_{\text{incl.}} = (4.19 \pm 0.12^{+0.11}_{-0.12}) \times 10^{-3}$$

$$|V_{ub}|_{\text{excl.}} = (3.51 \pm 0.12) \times 10^{-3}$$

$\sim 3\sigma$ tension for each
$(|V_{cb}|, |V_{ub}|)$

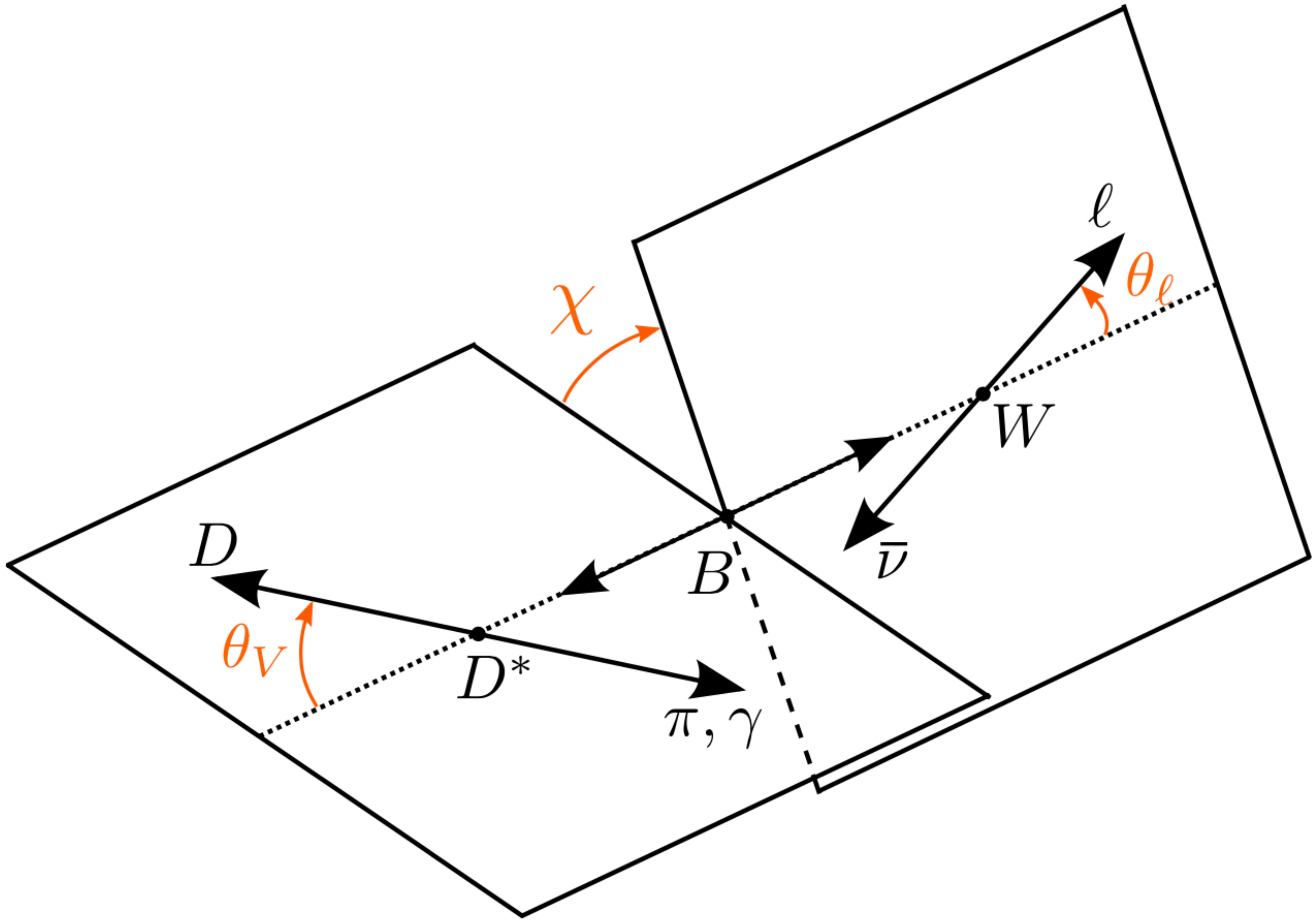
$$|V_{cb}|_{\text{excl.}} = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{cb}|_{\text{incl.}} = (42.19 \pm 0.78) \times 10^{-3}$$

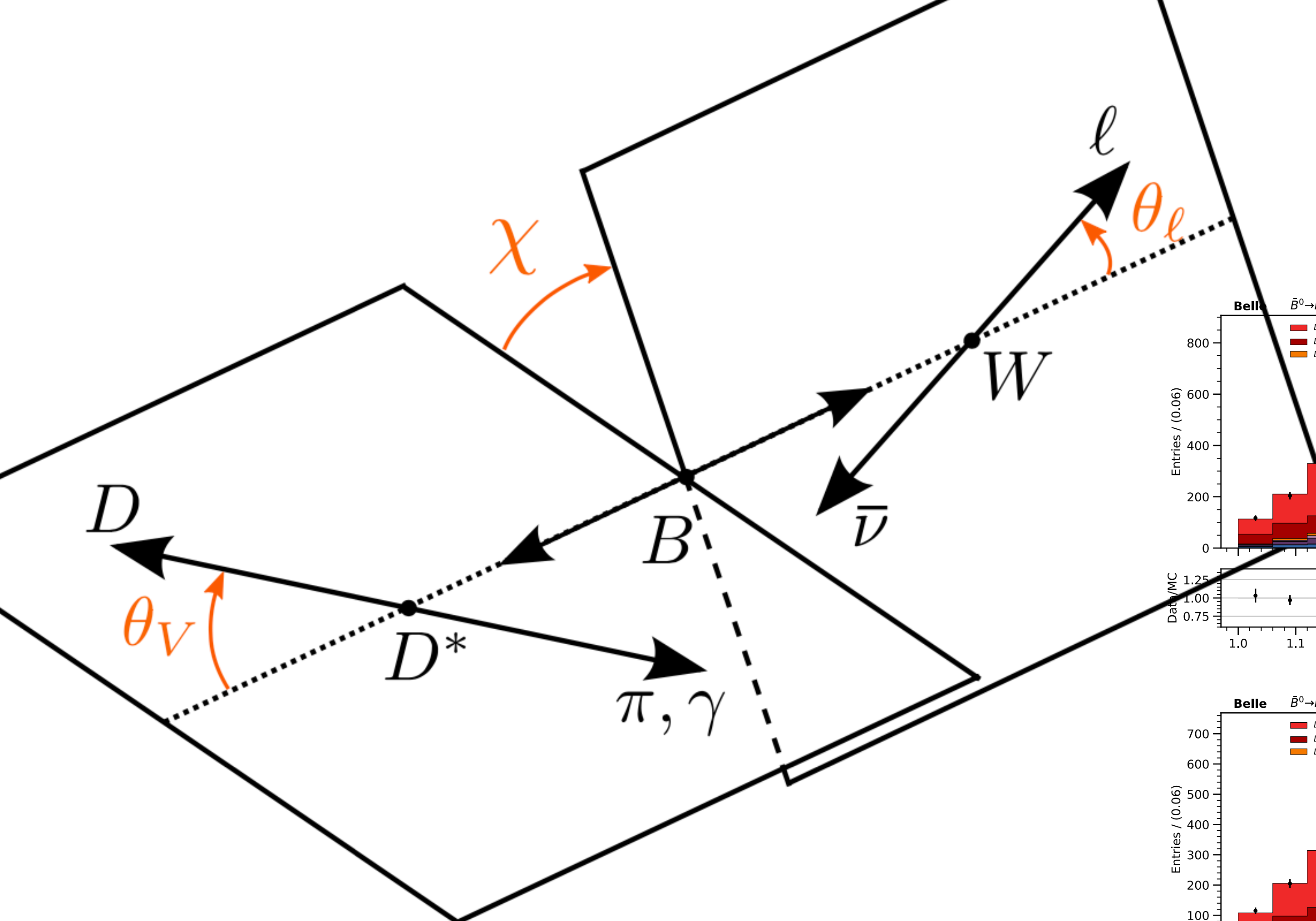
Measurement of Differential Distributions of $B \to D^* \ell \bar{\nu}_\ell$ and Implications on $|V_{cb}|$

Abstract

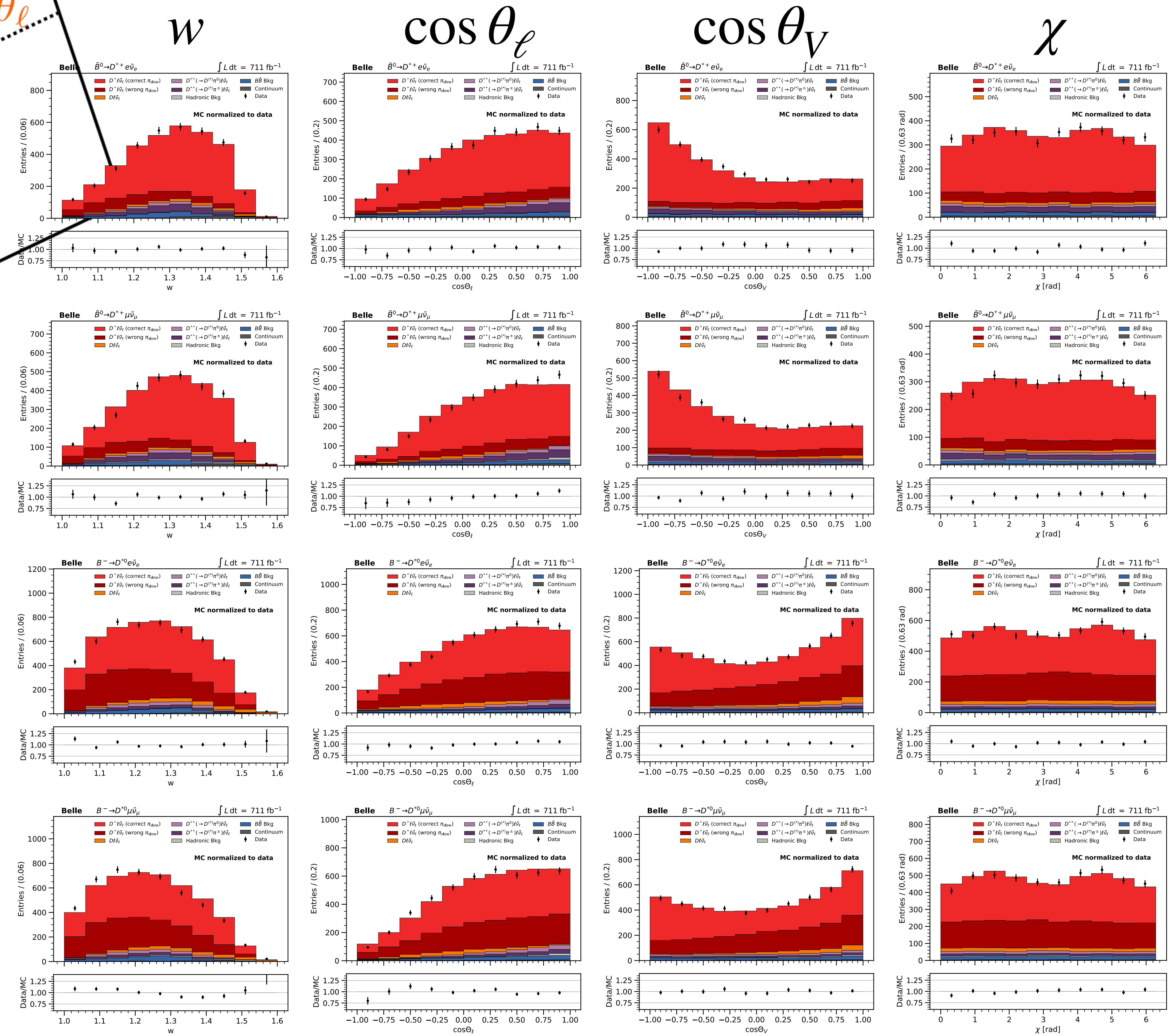
We present a measurement of the differential shapes of exclusive $B \to D^* \ell \bar{\nu}_\ell$ ($B = B^-, \bar{B}^0$ and $\ell = e, \mu$) decays with hadronic tag-side reconstruction for the full Belle data set of $711\,\mathrm{fb}^{-1}$ integrated luminosity. We extract the Caprini-Lellouch-Neubert (CLN) and Boyd-Grinstein-Lebed (BGL) form factor parameters and use an external input for the absolute branching fractions to determine the Cabibbo-Kobayashi-Maskawa matrix element and find $|V_{cb}|_{\mathrm{CLN}} = (40.1 \pm 0.9) \times 10^{-3}$ and $|V_{cb}|_{\mathrm{BGL}} = (40.6 \pm 0.9) \times 10^{-3}$ with the zero-recoil lattice QCD point $\mathcal{F}(1) = 0.906 \pm 0.013$. We also perform a study of the impact of preliminary beyond zero-recoil lattice QCD calculations on the $|V_{cb}|$ determinations. Additionally, we present the lepton flavor universality ratio $R_{e\mu} = \mathcal{B}(B \to D^* e \bar{\nu}_e)/\mathcal{B}(B \to D^* \mu \bar{\nu}_\mu) = 0.990 \pm 0.021 \pm 0.023$, the electron and muon forward-backward asymmetry and their difference $\Delta A_{FB} = 0.022 \pm 0.026 \pm 0.007$, and the electron and muon D^* longitudinal polarization fraction and their difference $\Delta F_L^{D^*} = 0.034 \pm 0.024 \pm 0.007$. The uncertainties quoted correspond to the statistical and systematic uncertainties, respectively.



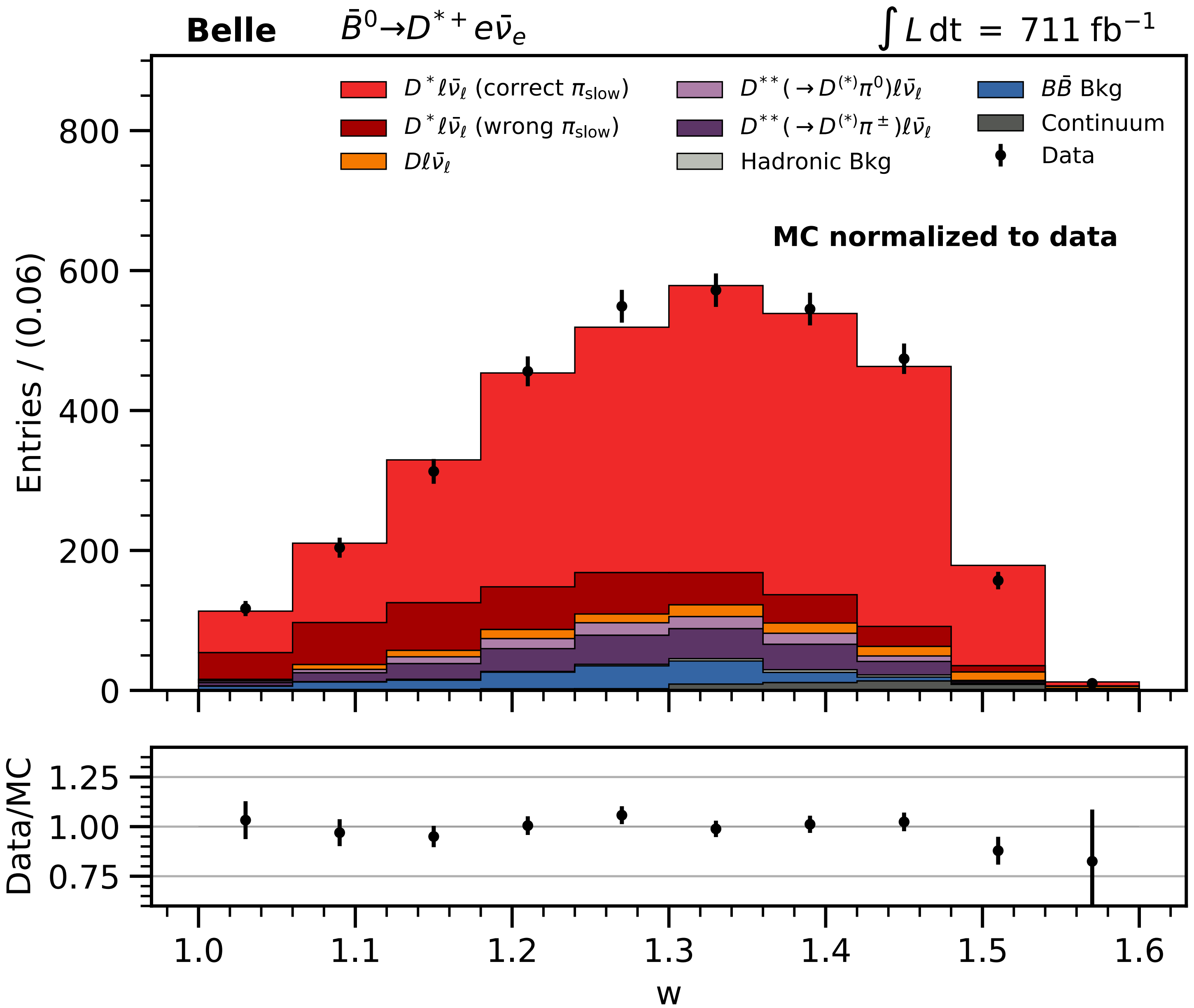
ℓ
θ_ℓ
χ
W
$\overline{\nu}$
D
B
θ_V
D^*
π, γ



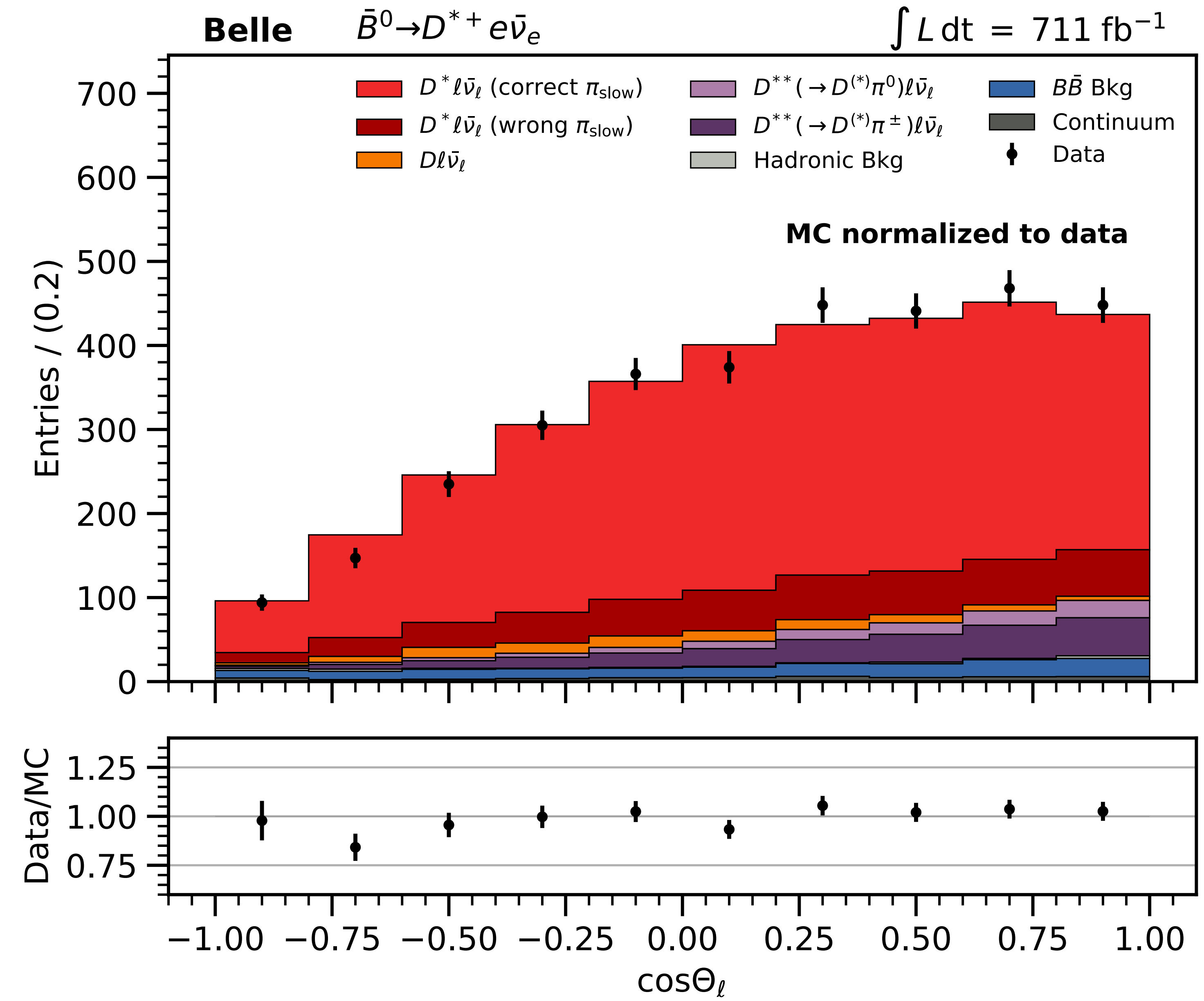
$$w = v \cdot v'$$
$$= \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

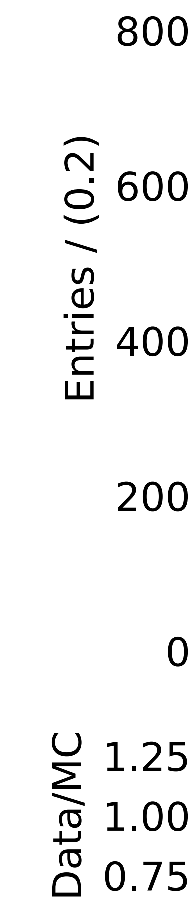


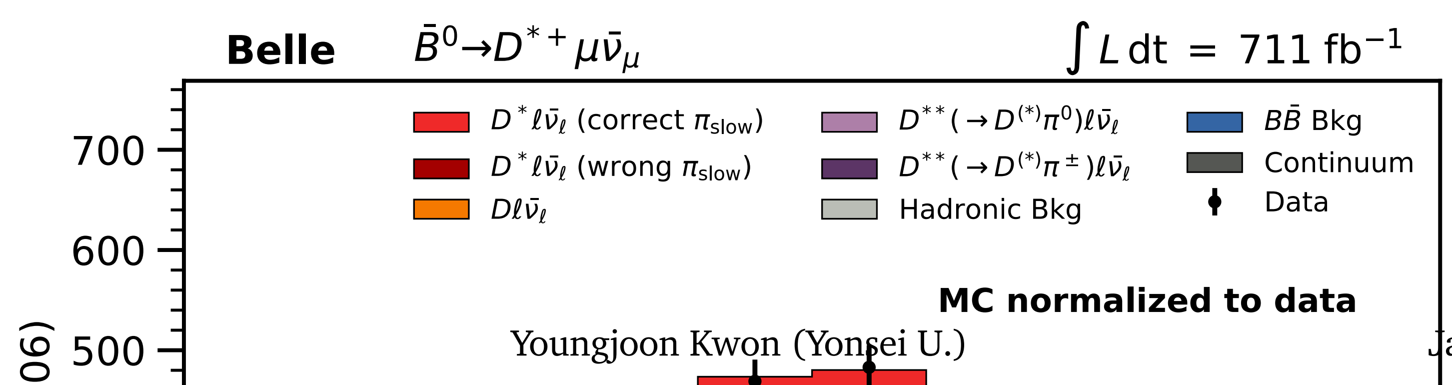
w

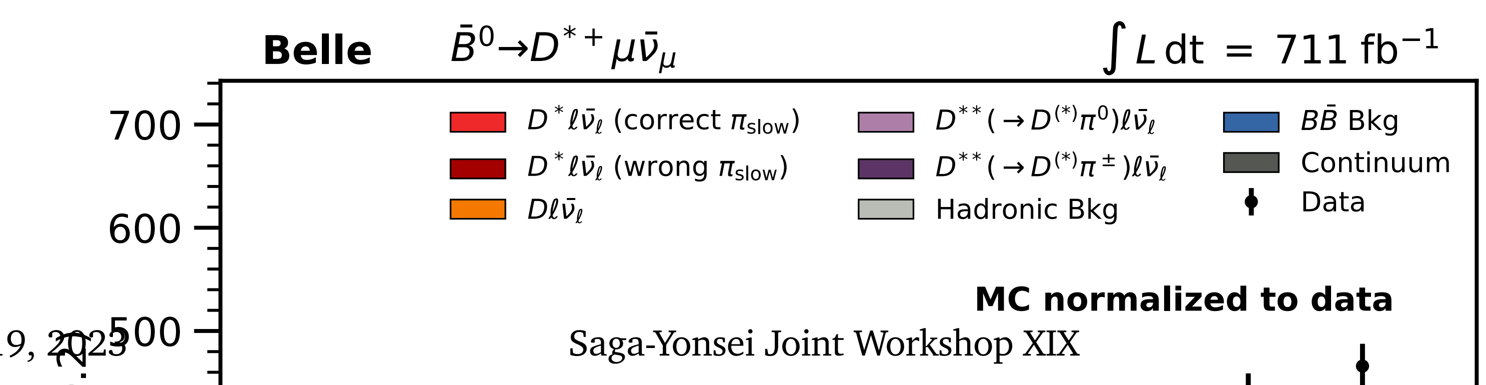


$\cos\theta_\ell$

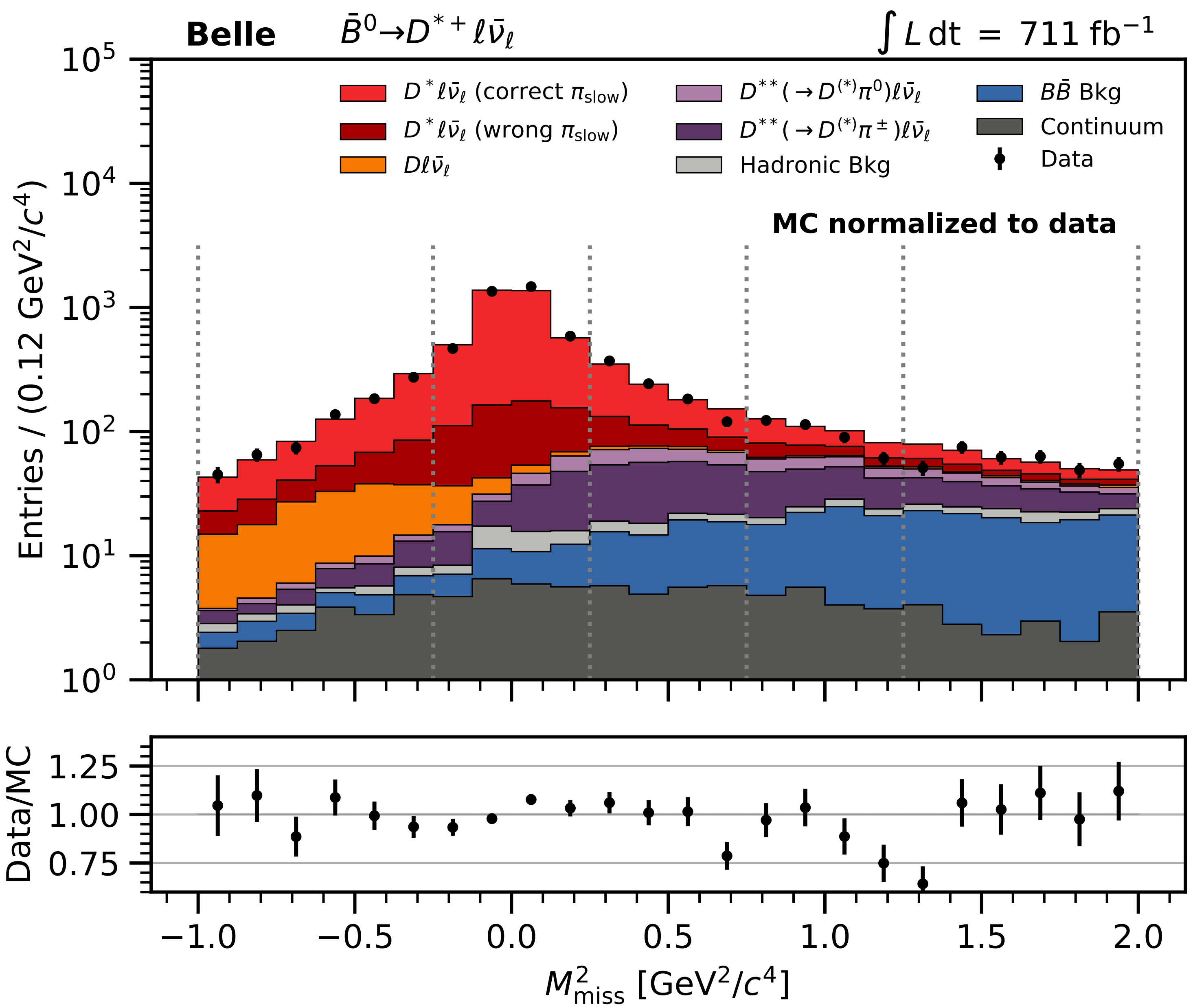


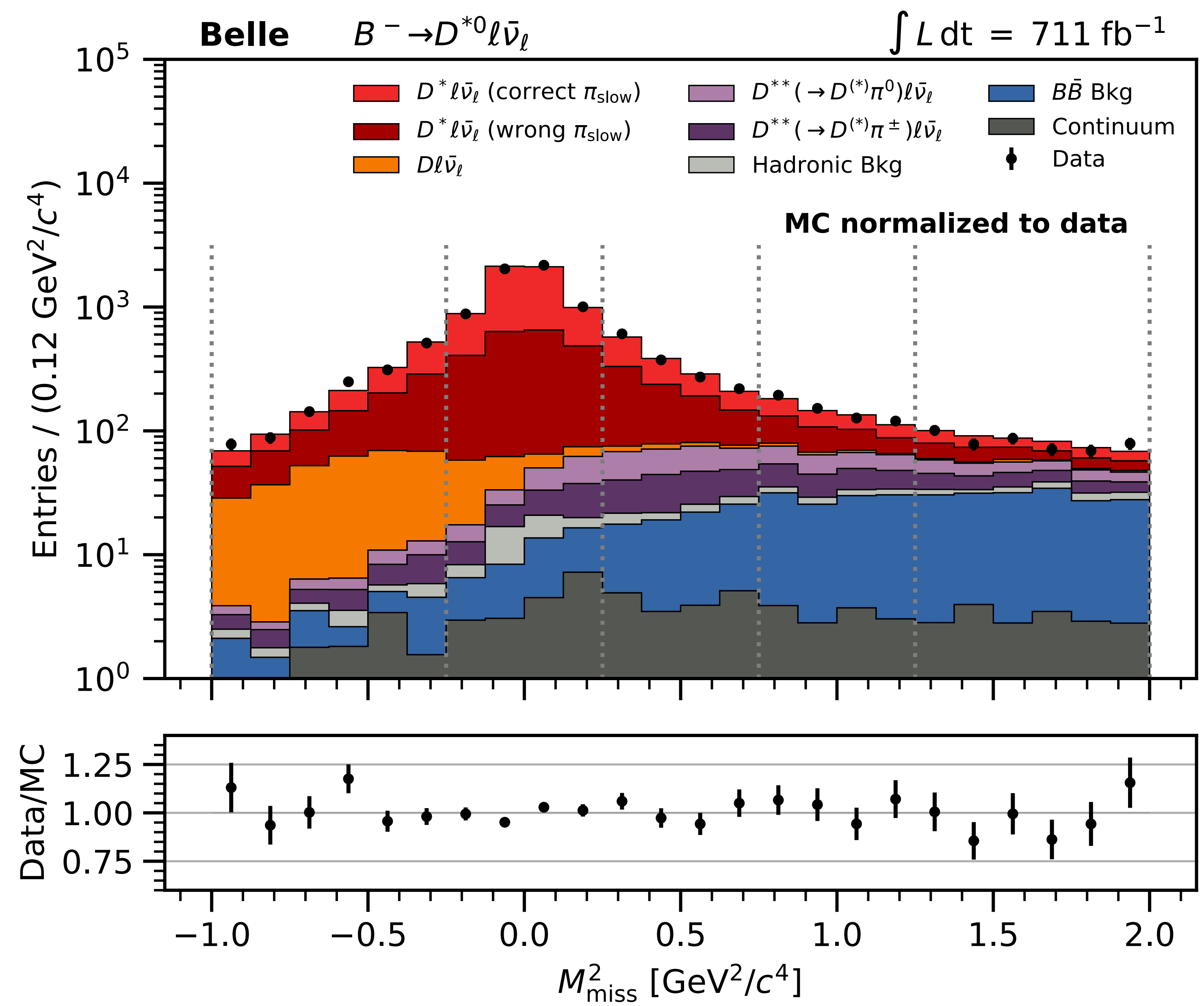






background subtraction, with binned likelihood fits to $M^2_{\rm miss}$





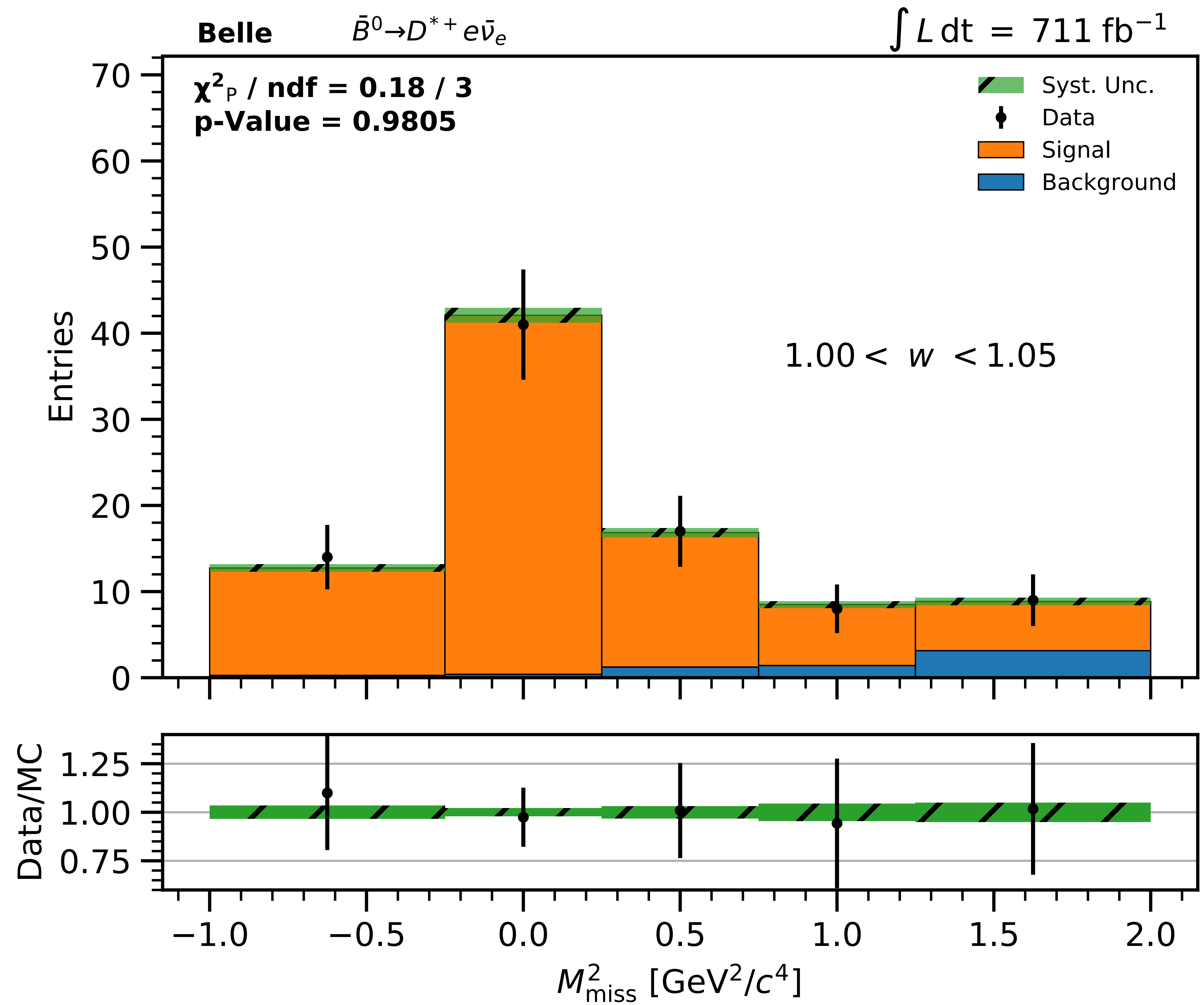
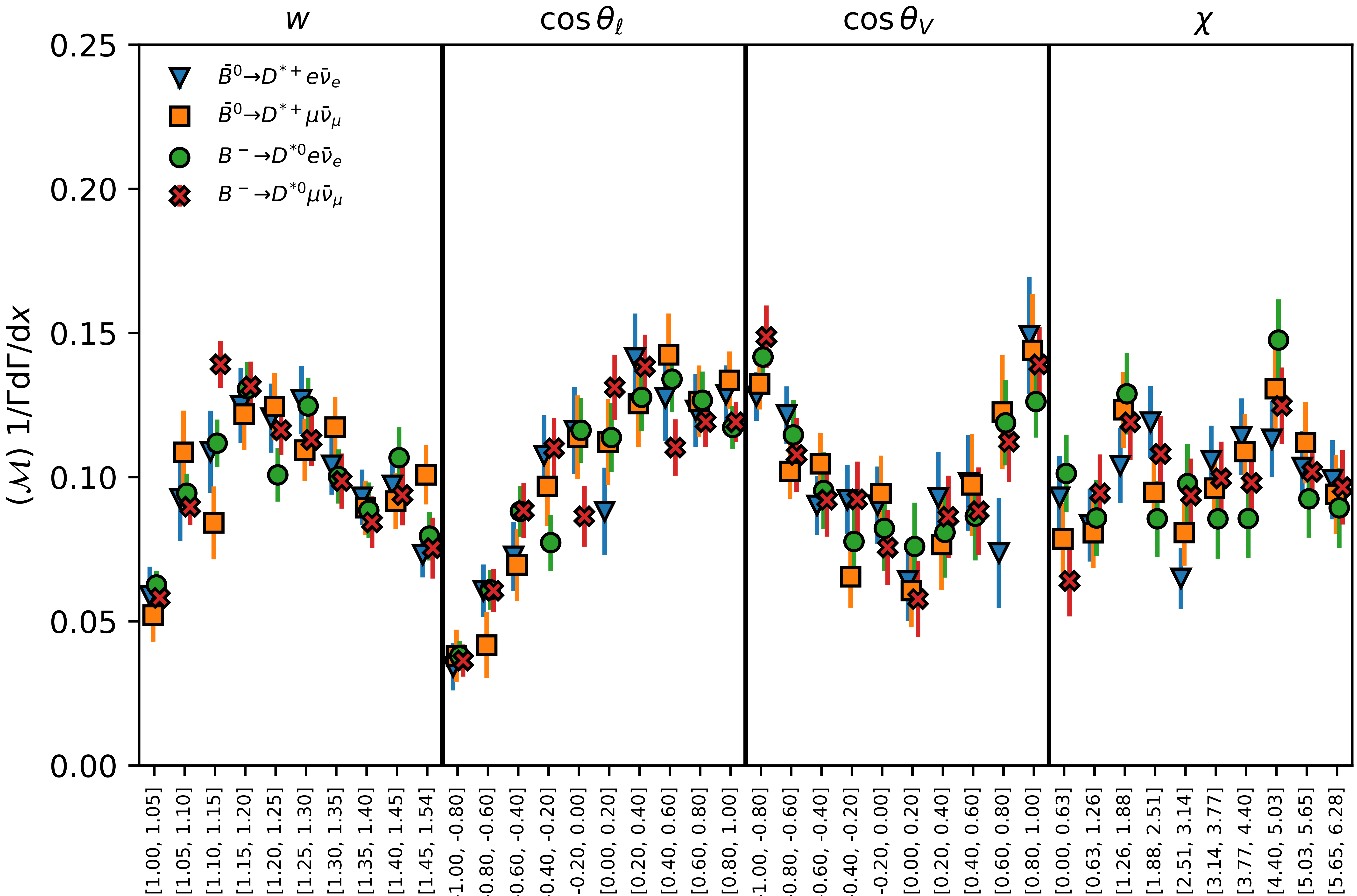


FIG. 4. The post-fit M^2_{miss} distribution in the $\bar{B}^0 \to D^* e \bar{\nu}_e$ mode, in the $1 < w < 1.05$ bin.

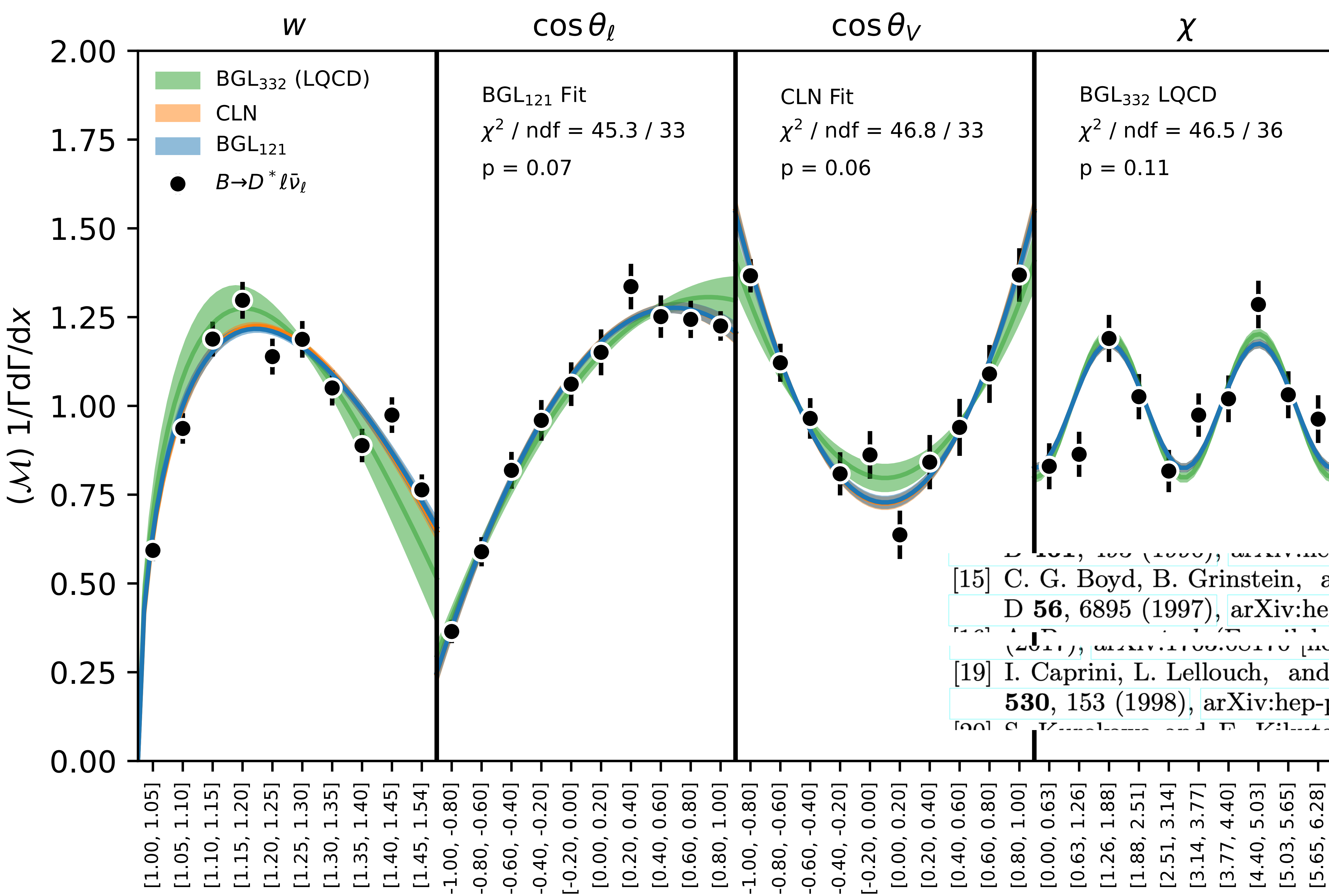
TABLE I. Normalized partial branching ratios $\Delta\Gamma$ in the observed bin Δx and the corresponding uncertainties for all channels and projections.

		$\bar{B}^0 \to D^{*+} e \bar{\nu}_e$		$\bar{B}^0 \to D^{*+} \mu \bar{\nu}_\mu$		$B^- \to D^{*0} e \bar{\nu}_e$		$B^- \to D^{*0} \mu \bar{\nu}_\mu$	
		$\Delta\Gamma/\Delta x$	σ	$\Delta\Gamma/\Delta x$	σ	$\Delta\Gamma/\Delta x$	σ	$\Delta\Gamma/\Delta x$	σ
Projection	Bin								
w	[1.00, 1.05)	0.059	0.010	0.052	0.009	0.063	0.005	0.058	0.004
	[1.05, 1.10)	0.092	0.015	0.109	0.014	0.094	0.007	0.090	0.006
	[1.10, 1.15)	0.109	0.014	0.084	0.013	0.112	0.008	0.139	0.008
	[1.15, 1.20)	0.125	0.013	0.122	0.012	0.131	0.009	0.131	0.009
	[1.20, 1.25)	0.120	0.012	0.124	0.012	0.101	0.009	0.116	0.009
	[1.25, 1.30)	0.127	0.012	0.109	0.011	0.125	0.010	0.113	0.009
	[1.30, 1.35)	0.104	0.010	0.117	0.010	0.100	0.009	0.099	0.010
	[1.35, 1.40)	0.093	0.010	0.089	0.009	0.088	0.010	0.084	0.009
	[1.40, 1.45)	0.097	0.009	0.092	0.010	0.107	0.011	0.094	0.010
	[1.45, 1.51)	0.073	0.008	0.101	0.010	0.080	0.008	0.075	0.011
$\cos\theta_\ell$	[-1.00, -0.80)	0.034	0.008	0.038	0.009	0.038	0.005	0.036	0.006
	[-0.80, -0.60)	0.061	0.009	0.042	0.011	0.061	0.007	0.061	0.008
	[-0.60, -0.40)	0.073	0.012	0.070	0.013	0.088	0.009	0.088	0.010
	[-0.40, -0.20)	0.108	0.014	0.097	0.014	0.077	0.010	0.110	0.011

fitted shapes (normalized)



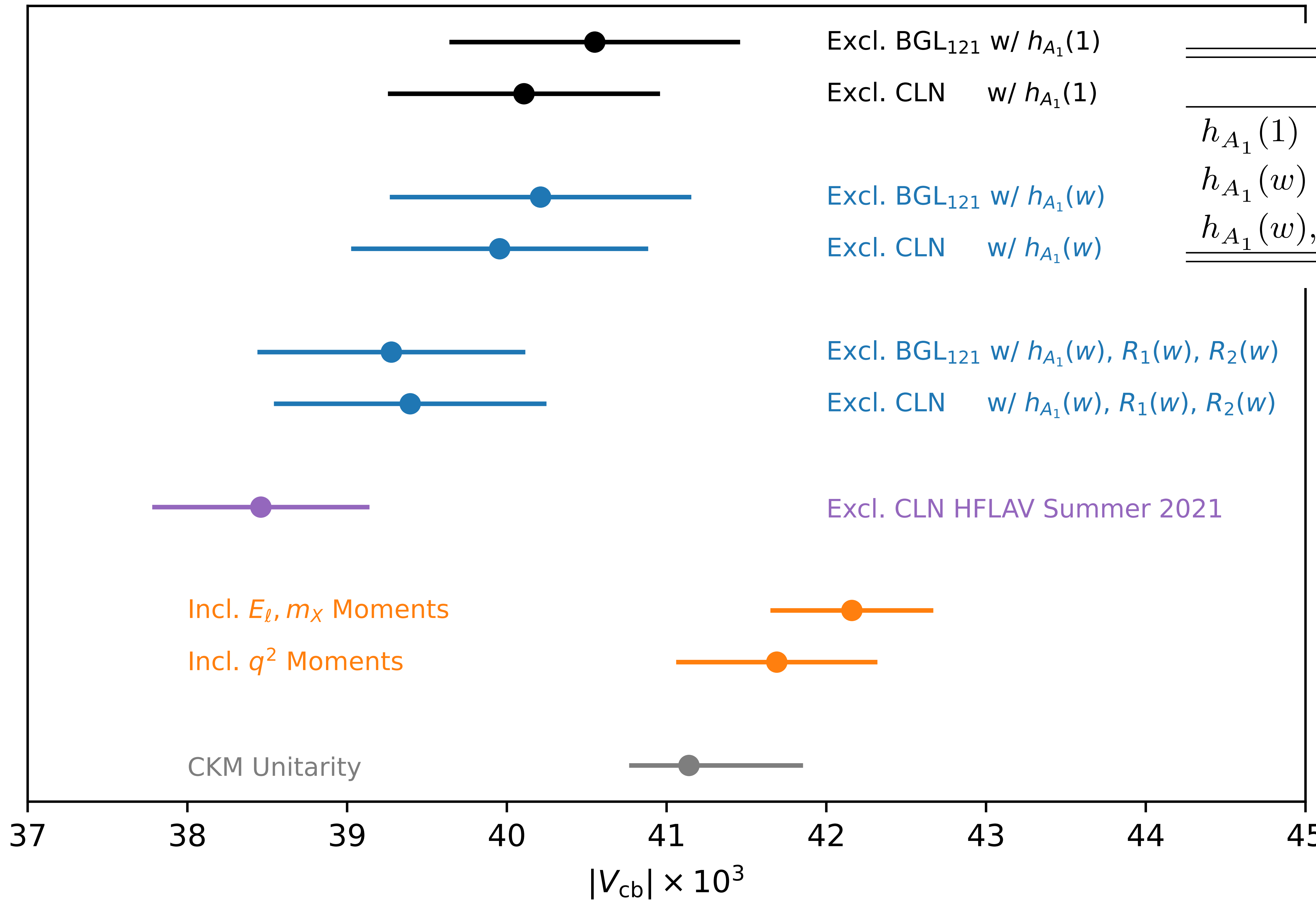
fitted shapes to BGL & CLN models



[15] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997), arXiv:hep-ph/9705252.

[19] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530**, 153 (1998), arXiv:hep-ph/9712417.

Results on $|V_{cb}|$



	BGL$_{121}$	CLN
$h_{A_1}(1)$	40.6 ± 0.9	40.1 ± 0.9
$h_{A_1}(w)$	40.2 ± 0.9	40.0 ± 0.9
$h_{A_1}(w),\ R_1(w),\ R_2(w)$	39.3 ± 0.8	39.4 ± 0.9

Other results

$$\Delta A_{\rm FB} = A^{\mu}_{\rm FB} - A^{e}_{\rm FB}$$

	$\Delta A_{\rm FB}$
$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.062 \pm 0.044 \pm 0.011$
$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$-0.003 \pm 0.033 \pm 0.009$
$B \to D^{*}\ell\bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

$$\Delta F_L = F^{\mu}_L - F^{e}_L$$

	$\Delta F_L^{D^*}$
$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.032 \pm 0.033 \pm 0.010$
$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$0.025 \pm 0.035 \pm 0.010$
$B \to D^{*}\ell\bar{\nu}_\ell$	$0.034 \pm 0.024 \pm 0.007$

$$R_{e\mu} = \frac{\mathcal{B}(B \to D^* e\bar{\nu}_e)}{\mathcal{B}(B \to D^* \mu\bar{\nu}_\mu)}$$

$$= 0.990 \pm 0.021 \pm 0.023$$

Epilogue

- In the pre-LHC, pre-Higgs era (the 1st decade of 21C), the main physics goal of e+e- B-factories was to observe CPV in B and test KM mechanism.
- Even with the discovery of Higgs, the question of flavor still remains.

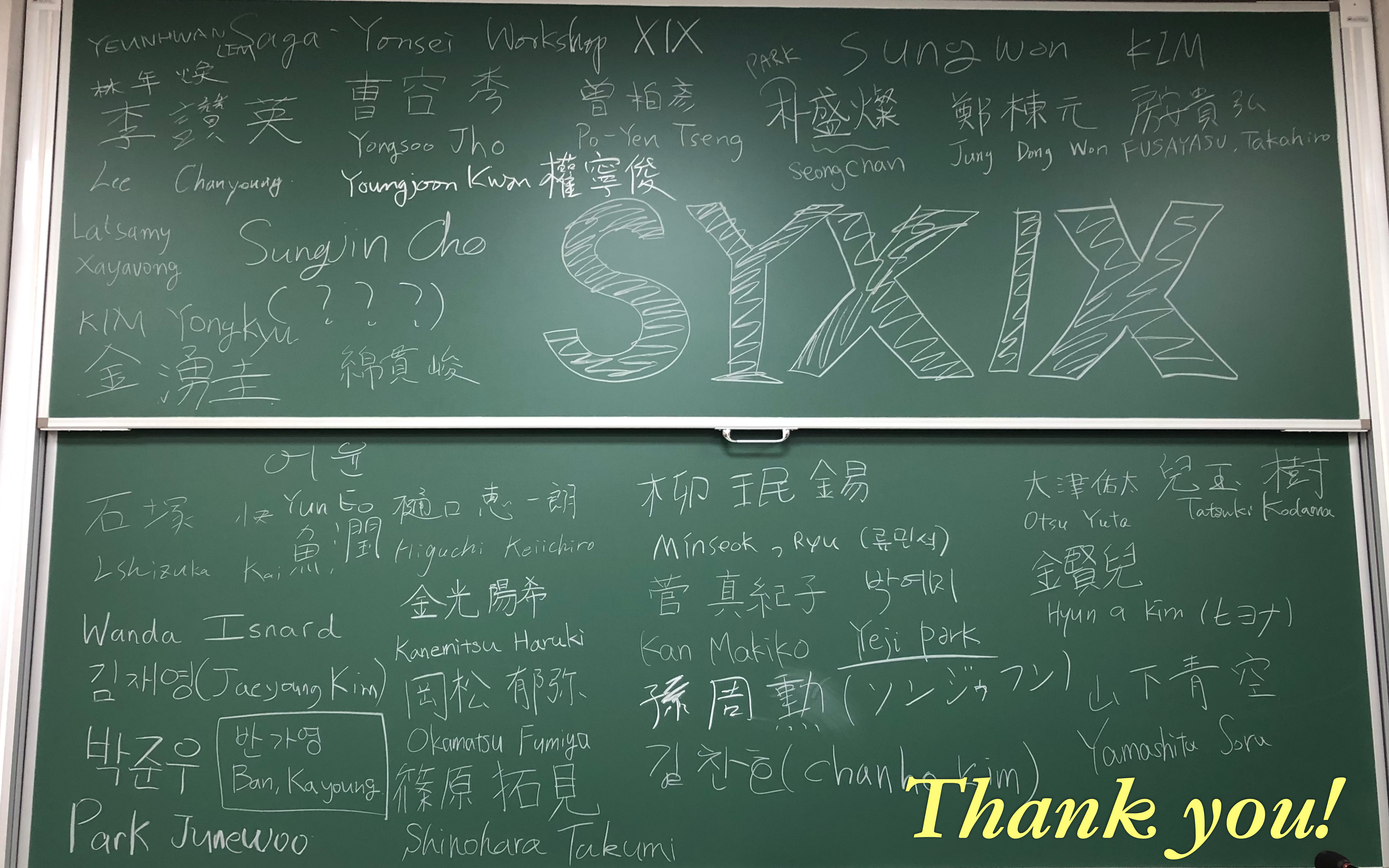
*"There must be something in the flavors. We just don't know where we can find it and what its scale is."**

"We shall not cease from exploration"†

- In this talk, we showed a recent Belle result that has relevance on the 'inclusive vs. exclusive tension' on CKM matrix elements
- With the Belle II, the exploration shall continue.
- And, enjoy the following two talks by two of the promising young Belle II colleagues!

---

* In a private conversation with Tao Han
† T. S. Eliot



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鄭棟元
Jung Dong Won
FUSAYASU, Takahiro
Lee Chanyoung
Youngjoon Kwon 權寧俊
Latsamy Xayavong
Sungjin Cho
KIM Yongkyu
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Ban, Kayoung
篠原拓見
Shinohara Takumi
김찬희
Park Junewoo
Thank you!